MITNE-262

# ACTIVITIES IN NUCLEAR ENGINEERING AT MIT

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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Prepared by the Staff of the

Nuclear Engineering Department

Massachusetts Institute of Technology

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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# 1. INTRODUCTION

## 1.1 Academic

This report has been prepared by the personnel of the Nuclear Engineering Department at M.I.T. to provide a summary and guide to the Department's educational, research and other activities. Information is presented on the Department's facilities, faculty, personnel, and students. This information has been prepared for the use of the Departmental Visiting Committee, past and present students, prospective students interested in applying for admission to the Department, and others.

The Department of Nuclear Engineering conducts teaching and research in both the fusion and fission areas. In fission both the problems of present day fission reactors as well as future generation reactors are being investigated. Every attempt is made to provide the student with courses and research opportunities that will prepare him or her with the basic education needed to pursue a career in this evolving industry.

Employment opportunities have remained excellent for nuclear engineers at all degree levels. There are three basic reasons for this high demand. First, despite the lack of new plant orders, there are currently over 70 plants under construction by utilities which have an increasing need for nuclear engineering staffs. Second, as a result of the continuing analysis of the Three Mile Island Unit II accident, maintenance and upgrading of operating plants has required an increased number of personnel with nuclear engineering training. And, third, graduates are required to support the national research effort for fusion and advanced fission reactor concepts.

In addition to the fission and fusion areas, the radiation science and technology area has become an area of increased activity within the Department since the last Activities Report. The technical specialties comprising this area include condensed matter physics, radiological (biomedical) sciences, health radiation physics, and materials science. The faculty in this area presently consists of eight professors and approximately 15 students.

At a time when many nuclear engineering departments are having difficulty meeting their enrollment goals the Department has been able to maintain its graduate enrollment at its goal of between 150 and 160 students. In this graduate population we have seen an increase in the fraction of students choosing the fusion option. However, the undergraduates choosing nuclear engineering during this year dropped to five students compared to eight last year. The total undergraduate enrollment is currently 27 students, well below our goal of 70 to 80.

The Department awarded 78 advanced degrees including 29 doctorates, 11 nuclear engineers, and 38 masters of science during the 1983-84 academic year. Eight bachelor degrees were awarded, four of which were joint SM/BS degrees.

Table 1

Enrollment in M.I.T. Nuclear Engineering Department

Fall Semester*

| | |
|---|---|
| 1972 | 115 |
| 1973 | 127 |
| 1974 | 138 |
| 1975 | 202 |
| 1976 | 221 |
| 1977 | 217 |
| 1978 | 213 |
| 1979 | 209 |
| 1980 | 189 |
| 1981 | 191 |
| 1982 | 197 |
| 1983 | 194 |

*Source: Bruce Report, July 1984 (for AY 1972 - 1982)

Table 2

Applications for Graduate Admission to M.I.T. Nuclear Engineering Department

Fall Semester

| | |
|---|---|
| 1972 | 88 |
| 1973 | 102 |
| 1974 | 128 |
| 1975 | 149 |
| 1976 | 136 |
| 1977 | 139 |
| 1978 | 123 |
| 1979 | 105 |
| 1980 | 114 |
| 1981 | 99 |
| 1982 | 123 |
| 1983 | 85 |
| 1984 | 81 |

## 1.2 Financial

The Nuclear Engineering Department conducts research in the areas of 1) Fission Reactors (Reactor Engineering, Reactor Physics & Fuel Management, Nuclear Materials, and Reliability & Risk Analysis), 2) Controlled Fusion (Applied Plasma Physics and Fusion Reactor Technology), 3) Radiation Physics, including Biomedical Applications (Condensed Matter Sciences, Biomedical and Radiological Sciences), and 4) Energy Technology and Resources. During the fiscal year ending June 30, 1984, departmental faculty supervised a research volume of approximately $3,329,722, including research administered through the Departments of Nuclear Engineering and Materials Science and Engineering, as well as the MIT Energy Laboratory, the Materials Processing Center, the Harvard/MIT Division of Health Sciences and Technology, the Whitaker College of Health Sciences, Technology and Management, the Nuclear Reactor Laboratory, the Plasma Fusion Center, and the Research Laboratory of Electronics.

During the fiscal year 1984 approximately 73% of our graduate student body was appointed to the graduate student staff, receiving financial aid in the form of full and part-time research and teaching assistantships. Other departmental financial aid is available to graduate students in Nuclear Engineering in the form of two MIT-endowed tuitionships, three departmental administered fellowships -- the Sherman R. Knapp Fellowship (Northeast Utilities), the Theos J. Thompson Memorial Fellowship, the Manson Benedict Fellowship -- and through graduate school allocations to the Nuclear Engineering Department from the College Work Study Program.

Other scholarship support for the FY84 was derived from the Charles Stark Draper Lab, Inc., NUS Corporation, Jerry McAfee Chair, Schlumberger Doll Research Center, Consumers Power Co., International Business Machines Corporation, the United States Department of Energy, Hertz Foundation, National Science Foundation, Rockwell International, National Aeronautics and Space Administration, Graduate Engineering Minority, and ACF Foundation, Inc.

## 1.3 Organization of Activities Report

In Section 2 of this report there is a discussion of developments within the Department since September 1981. Section 3 is a detailed discussion of our research and educational activities. Section 4 presents a discussion of our curriculum, including the S.B. program. Section 5 discusses the facilities of the Department. In Section 6 there is a summary of Departmental personnel. Sections 7 and 8 provide statistical information about the Department and its students. The final section, 9, is a listing of theses completed since our last report.

## 2. SUMMARY OF DEVELOPMENTS SINCE SEPTEMBER 1981

This section is a summary and discussion of developments within the Department since our previous report. The summary includes academic programs, special summer activities, the Department's contribution to the Institute-at-large, outside professional activities, changes in the faculty, and recent honors to the faculty.

A major new project in the area of nuclear power plant design innovation has been initiated by several members of the Department faculty. These include Professors Lester, Driscoll, Golay, Lanning, Lidsky, Rasmussen, and Todreas. The general objective of this project is to explore the role of nuclear power plant design innovations in increasing the attractiveness of the nuclear option to US electric utilities in the 1990's.

There have been several changes in our academic program during the past few years. A Radiological Sciences Doctoral Program, under the direction of Professors Gordon Brownell and Alan Nelson, was introduced during the academic year 1982-83. The objective of this program is to educate students in the various applications of radiation in medicine and correspondingly to expand the research frontiers in this area. Academic and research objectives may be pursued in one of three specialty areas: medical therapy, imaging and diagnostic technology, and radiation biophysics. This program is currently supported by the National Institutes of Health (NIH).

During the academic year 1983-84, a master's program was initiated in the area of health radiation physics. This program, developed by Professor Otto Harling, is designed to combine a strong engineering background with course work and thesis research in the principles of radiobiology, radiation dosimetry, radiation measurement and radiation risk exposure management. The MIT Reactor, the Bates Accelerator, and various facilities in Boston-area teaching hospitals provide significant experience in radiation management. A new laboratory course, Health Physics II, was developed to complement the recommended course curriculum. A nuclear utility provided fellowship support for one student during the first year.

The Engineering Internship Program, which offers undergraduates the opportunity to have on-the-job experience as part of their overall education, has been successful since it was initiated in the summer of 1978. A total of nine students -- two graduates, four seniors, and three juniors -- are now in the program. Companies which have placed students from the Nuclear Engineering Department include Brookhaven National Laboratory, Commonwealth Edison, EG&G Idaho, Stone & Webster Engineering Corporation, and Los Alamos National Laboratory. This program is described in Section 4.8.

During the summers of 1982, 1983, and 1984, the Department offered a special summer program on "Nuclear Power Reactor Safety," directed by Professors Norman Rasmussen and Neil Todreas. Each summer this two-week program has been well attended by members of the U.S. nuclear industry as well as members of the international community. The summer session program, "Man-Machine Interfacing in Nuclear Power and Industrial Process Control," was offered once again in June 1982 as a joint effort with the Department of Mechanical Engineering by Professors David Lanning and Thomas Sheridan. In June 1984, Professors Sheridan and Lanning offered a new program entitled, "Human Factors and Computer Aids in Nuclear Power and Industrial Control." Twelve people from five countries participated. In June 1982, Professor Carolyn Heising presented a new summer program entitled, "Probabilistic Risk Assessment: Uses and Applications to Decision-Making in the Nuclear Industry." Because this course was well received, it was offered once again during the summer of 1983.

In cooperation with the Center for Advanced Engineering Study Seminar Office, various faculty members coordinated and/or have participated in several mini-course offerings during the past few years. A three-day program on "Advances in Nuclear System Thermal Analysis" has been offered for the past two years under the direction of Professor Mujid Kazimi. Participants included outside lecturers as well as Professors Golay, Meyer, Rasmussen, and Todreas. Professor Heising helped coordinate and, along with Professor Rasmussen, participated in a program on "Reliability Analysis and Risk Assessments," offered for the first time in the spring of 1983. This effort was complemented by a fall 1982 ILP seminar on the same subject, coordinated by Professors Heising and Ernst Frankel from the Department of Ocean Engineering. A six-day course on "Light Water Reactor Design and Safety Analysis" was presented in May 1983. This program, coordinated by Dr. L.S. Tong, former director of safety research at the U.S. Nuclear Regulatory Commission, was attended by representatives of ten countries. Professors Ballinger and Driscoll participated in this course.

Professor Yip organized a two-week session on the use of atomistic simulations to study solid state diffusion. This workshop was sponsored jointly by NATO and the European Center for Atomic and Molecular Calculations and was held at the University of Paris, Orsay, France. Professor Harling planned a highly successful international symposium on the uses and development of low and medium flux research reactors. Participants from 21 centers, worldwide, presented over 140 papers which have been incorporated into a special volume of the international journal, Atomkernenergie-Kerntechnik.

Two nuclear workshops were held in the Energy Laboratory's Electric Utility Program which involved Department faculty. The workshop on LWR Longevity Extension was directed by Professor Golay; the session on Modular HTGR Technology was conducted by Professors Lidsky and Lester. Both sessions were well attended and aided in building constituencies for research programs in their respective areas.

The MIT Student Branch of the American Nuclear Society has been very productive since our last Activities Report. Activities have included departmental seminars, student/faculty meetings, departmental steak fries, and course evaluations. At the 29th annual meeting of the ANS held in June 1983, the MIT Student Branch was named a recipient of the Glasstone Award for the year 1983. This national award was presented to the members of the Student Branch for accomplishing notable achievements in public service and the advancement of nuclear engineering during the academic year.

Nuclear Engineering faculty members continue to be active outside the Department in both Institute and non-Institute related activities for professional societies, government and industry.

Professor Driscoll represented the US at the IAEA/AESJ-sponsored International Meeting on the Recovery of Uranium from Seawater, held in October 1983, in Tokyo, Japan. He also visited Taiwan in May 1984 to consult with INER, Taipower and Tsing Hua University on the nuclear fuel cycle at their invitation. During the spring term 1984, Professor Lanning was on half-time leave from MIT, in order to study the present status of the High Temperature Gas-Cooled Reactor Technology (HTGR) at GA Technologies in San Diego, California. Professor Rose continued his joint appointment with the East-West Center in Honolulu during the period January through April 1984. During this period he collaborated in a study of present and future electric power systems for the regions of east and southeast Asia, an activity involving the East-West Center, EPRI, MIT, and the principal electric power authorities of the region.

Professor Rasmussen continues to serve as Chairman of the MIT Committee on Reactor Safeguard, as well as Chairman of the MIT School of Engineering Committee on Energy Systems. He was recently appointed a member of the Ad Hoc Committee on Technology Policy and Society Studies at MIT. At the EG&G Idaho National Engineering Laboratory, he is Chairman of both the Scientific Review Committee and the Fusion Safety Committee. He also holds an appointment to the National Science Board. Professor Harling continues to serve as Director of the interdepartmental Nuclear Reactor Laboratory. Professor Lester chairs the MIT School of Engineering Committee on Energy Education. Professor Henry was selected a member of the MIT Advisory Committee on Shareholder Responsibility. He continues to represent the Department to the Committee on Graduate School Policy (CGSP). He is also the CGSP representative to the MIT Committee on Educational Policy. Professor Lanning continues as a member of the MIT Committee on Reactor Safeguard, the Safety Audit Committee at Northern States Power Co., the Nuclear Safety Review and Audit Committee at Boston Edison and the Source Term Review Group for Stone & Webster Engineering Corporation. The Nuclear Heat Transfer Committee of the American Institute of Chemical Engineering is chaired by Professor Kazimi. He is also on the Advisory Committee of the DOE Fellowship for Magnetic Fusion Energy Technology. Professor Freidberg continues on the Executive Committee of the Stellarator Advisory Panel for the DOE. He also serves as the Group Leader of the Theory and Computation Group at the Plasma Fusion Center. Professor Todreas continues to serve on the Executive Committee of the ANS. He also serves on the DOE-sponsored panel evaluating the National Light Water Reactor Research and Development Programs and as chairman of the EG&G TMI-2 Accident Analysis Industry Review Group. He is a member of the editorial board of the thermal design section of the Journal of Nuclear Engineering and Design. Professor Henry is a member of the editorial review board for Nuclear Science and Engineering. Professor Rose serves on the Advisory Committee of the Congressional Office of Technology Assessment. He is also a member of the American Association for the Advancement of Science's Committee on Climate. Professor Meyer is a member of the Review Committee for the Applied Physics Division at Argonne National Laboratory.

Since our last Activities Report there have been a number of changes in the faculty. Professors Mujid Kazimi and Kim Molvig were promoted to Associate Professors with tenure. Professor Richard Lester was promoted to Associate Professor.

In September 1983, Professor Ian Hutchinson joined the staff as an Associate Professor of Nuclear Engineering. His activities will be in the area of experimental plasma physics.

Professor Ronald Ballinger joined the staff as an Assistant Professor of Nuclear Engineering. This appointment is joint with the Department of Materials Science and Engineering. He specializes in the area of fatigue, corrosion fatigue, stress corrosion cracking behavior in nuclear systems, and fuel behavior modeling.

Professor Andrei Schor was appointed an Assistant Professor of Nuclear Engineering. His activities will be in the area of numerical methods in reactor analysis.

Professor Alan Nelson was appointed Director of the MIT Whitaker Laboratory of Microscopy.

Several of the Department faculty were recognized with honors during the past few years. The MIT Student Branch of the ANS bestowed their Outstanding Teacher Award upon Professor Jeffrey Freidberg for the academic year 1981-82. Professor Richard Lester was the recipient for 1982-83 and Professor Alan Nelson received this distinguished honor for the past year.

Professor Michael Driscoll was named the co-recipient of the Institute's Irwin Sizer Award for 1982 for "the most significant contribution to MIT education" in recognition of his efforts over the previous three years in the establishment of the Institute's writing requirement. Professor Alan Nelson was awarded the first Keck Professorship in Biomedical Engineering, an endowed chair sponsored by the William M. Keck Foundation for career development. Professor Norman Rasmussen was appointed the McAfee Professor of Engineering. He also received the Distinguished Alumni Award from Gettysburg College. Professor Manson Benedict received the Washington Award of the Western Society of Engineers.

Professor Neil Todreas was elected to the ANS Board of Directors and to the ANS Executive Committee. He was also selected a Fellow of the American Society of Mechanical Engineers. Professor Michael Driscoll was elected to the Executive Committee of the Fuel Cycle and Waste Management Division of the ANS. Professor Kent Hansen was elected to the National Academy of Engineering. The National Academy of Engineering named Professor David Rose to its Energy Engineering Board. Professor Rasmussen was selected to chair EPRI's Nuclear Accident Source Term Committee.

# 3. RESEARCH AND EDUCATIONAL ACTIVITIES

## 3.1 Reactor Physics

Reactor physics is concerned with the space, time and energy behavior of neutrons and neutron-induced reactions in nuclear reactors. While the numerical results differ from application to application as, say, between thermal and fast reactors, many of the experimental and calculational techniques used to study and define neutron and reaction behavior are basically similar. Furthermore, reactor physics and reactor engineering are closely interrelated. Consequently there is considerable overlap in the work described in the following sections.

### 3.1.1 Subjects of Instruction

The basic subjects of instruction in reactor physics include the undergraduate subject 22.021, Nuclear Reactor Physics, and the three graduate subjects, Nuclear Reactor Physics I, II, and III which are offered in a three-semester sequence.

22.021: Nuclear Reactor Physics, is an introduction to fission reactor physics covering reactions induced by neutrons, nuclear fission, slowing down of neutrons in infinite media, diffusion theory, the few-group approximation, and point kinetics. Emphasis is placed on the nuclear physics bases of reactor design and their relation to reactor engineering problems. Lectures are in common with 22.211; homework, exams, and recitation are separate.

22.211: Nuclear Reactor Physics I, is an introduction to problems of fission reactor physics covering nuclear reactions induced by neutrons, nuclear fission, slowing down of neutrons in infinite media, diffusion theory, the few group approximation, and point kinetics. Emphasis is placed on the nuclear physical bases of reactor design and their relation to reactor engineering problems.

22.212: Nuclear Reactor Physics II, deals with problems relating to the operation of nuclear reactors at power including few group and multigroup theory, heterogeneous reactors, control rods, poisons, depletion phenomena, and elementary neutron kinetics. Attention is directed to the application of reactor theory to actual reactor systems.

22.213: Nuclear Reactor Physics III, considers current methods for predicting neutron behavior in complex geometrical and material configurations. Emphasis is placed on the transport equation and methods for solving it, systematic derivation of group diffusion theory and homogenization, synthesis, finite element response matrix, and nodal techniques applied to reactor analysis.

Most undergraduate students in the Department take 22.021, and most graduate students take 22.211 and 22.212. Those whose special interests lie in the general area of nuclear reactor physics also take 22.213.

22.09: Introductory Nuclear Measurements Laboratory, deals with the basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis; introduction to electronics in nuclear instrumentation; counting experiments using Geiger-Muller counter, gas-filled proportional counter, scintillation counter and semiconductor detectors. A term project emphasizes applications to experimental neutron physics, radiation physics, health physics, and reactor technology.

22.29: Nuclear Measurements Laboratory, covers basic principles of interaction of nuclear radiations with matter. Principles underlying instrumental methods for detection and energy determination of gamma-rays, neutrons and charged particles are discussed. Other topics include applications to applied radiation physics, health physics, and reactor technology; laboratory experiments on gas-filled, scintillation, and semiconductor detectors; nuclear electronics such as pulse amplifiers, multi-channel analysers and coincidence techniques; applications to neutron activation analysis, X-ray fluorescence analysis, thermal neutron cross sections, and radiation dosimetry.

22.35: Nuclear Fuel Management, characterizes the space-time history of nuclear fuels and the effects upon fuel costs. Topics covered include physical and material constraints upon fuels and their effects on fuel management policies; methods of analysis for the optimization of fuel costs; and a qualitative description of current methods of management and areas of future development.

22.41: Numerical Methods of Radiation Transport, deals with the mathematical methods for the solution of neutron/photon transport problems: detailed developent of discrete ordinates and Monte Carlo methods for applications in radiation shielding. Discussion of iteration techniques for solution of coupled difference equations. Group projects on solving original transport problems by design and implementation of computer codes are required.

22.42: Numerical Methods in Engineering Analysis, is a subject in numerical and mathematical methods which deals with analytic and numerical methods useful in solving problems in reactor physics. Review of specific mathematical techniques for solving engineering problems including linear algebra, finite difference equations, and numerical solution of equations. Special topics such as multigroup diffusion methods.

22.43: Advanced Numerical Methods in Engineering Analysis, covers advanced computational methods used in analysis of nuclear reactor engineering problem studies. Emphasizes the solution of multidimensional problems and non-linear equations using modern iterative techniques. Topics include finite difference and finite elements formulations with applications to incompressible and compressible flows. Introduction to numerical turbulence modeling. Additional special topics covered depending on the interests of the class.

### 3.1.2 Reactor Physics Research

The long-range goal of the theoretical work on reactor physics being carried out in the Department is to increase the accuracy and/or decrease the cost of analyzing the behavior of large power reactors. Since the application is more immediate and since the calculations are both cheaper to perform and more challenging to the method, specific developments are usually carried out and tested for thermal reactors. However, many of the ideas apply equally well to fast reactor systems. The ultimate goal is to develop a practical capability to analyze space-dependent nuclear phenomena throughout lifetime under both static and dynamic conditions. Very real progress towards reaching that goal has been made.

#### (1) Nodal Schemes

If, for purposes of obtaining critical eigenvalue and gross power distributions, a reactor can be represented as composed of large homogeneous nodes, there is no need to compute flux distributions throughout the nodes. Since physically real heterogeneities have been homogenized in the mathematical model, average reaction rates are the only calculated quantities having a true physical significance. Finite difference methods provide a very wasteful way of analyzing such a reactor, since many mesh points must be used in a node to insure accuracy of the average nodal fluxes; yet, once the full core solution is obtained all the extra information specifying detailed flux shapes in the nodes is simply integrated out. Nodal methods circumvent this difficulty by treating the average nodal fluxes themselves directly as unknowns. Calculations are faster both because there are many fewer unknowns and because (with few unknowns) it becomes practical to use more powerful numerical iteration schemes. This situation makes it practical to solve three-dimensional reactor problems for both static and transient situations.

Because of the advantages just cited we have developed a two-group nodal method, embodied in the computer code QUANDRY, as the main framework for our analysis of thermal reactor problems. Production versions of that code are now being created at N.U.S. and at Brookhaven (with EPRI support). We have recently developed a preliminary two-dimensional hexagonal-geometry version at MIT.

If global flux distributions are to computed by a nodal scheme, it is necessary to develop procedures for obtaining the homogenized cross sections that characterize the nuclear properties of the nodes. In addition, if local fuel-pin powers are desired, it is necessary to develop a "dehomogenization" procedure so that detailed, heterogeneous flux shapes can be recaptured from node-averaged values. The resolution of these problems is discussed in the next two sections.

#### (2) Homogenization Methods

The derivation of the QUANDRY nodal equations starts from a group diffusion theory model of a reactor composed of nuclearly homogeneous nodes. Hence before QUANDRY can be used it is necessary to find homogenized group diffusion theory parameters that reproduce correctly the average reaction rates and neutron leakage rates of the actual heterogeneous nodal zones making up the reactor.

To find such parameters we have developed a variant of a method suggested by Koebke in which the flux for the homogenized model is permitted to be discontinuous across nodal interfaces. If the proper discontinuity factors are known, the scheme will reproduce exactly the average leakage and reaction rates for each node in the reactor.

To find exact discontinuity factors is self-defeating since, to do so, it is necessary to know in advance the average leakage and reaction rates of the heterogeneous core. However, it has been found that the discontinuity factors are not very sensitive to the current boundary conditions on the nodal surfaces, and this fact suggests that it may be possible to estimate them, along with the homogenized group cross sections, by performing local calculations for the heterogeneous node alone or for that node and its nearest neighbors.

The simplest procedure for carrying out such local calculations is to impose zero-net-current boundary conditions on an isolated assembly. For unrodded, interior assemblies, these "assembly" discontinuity factors and homogenized cross sections (ADF's and AXS's) lead to predictions of nodal power that differ from reference calculations by less than one percent. However, for rodded assemblies or assemblies next to the reflector, more elaborate calculations are required.

An iterative procedure has been developed for these cases: the first estimate of currents across nodal surfaces is made using ADF's and AXS's in QUANDRY, and the non-zero currents resulting from that QUANDRY run are in turn used to find more accurate discontinuity factors and homogenized group parameters for a second QUANDRY calculation, and the iteration process is continued to convergence. The scheme has been found to yield excellent results. However, the cost of recomputing the discontinuity factors at each iteration for each assembly (done by using response matrices) is very high. Accordingly we have lately concentrated effort on non-iterative procedures.

The best non-iterative procedure we have found for determining discontinuity factors and homogenized group parameters for reactor nodes is to use values computed from "color sets". A color set is an assembly-sized node composed of 4 different <u>quarter</u>-assembly regions. We have generalized the usual color set configurations to include quarter-assembly-sized regions composed of baffle-reflector material so that discontinuity factors across core-reflector interfaces can be estimated accurately.

When, for two- and three-dimensional PWR benchmark problems, color set calculations are used for PWR's to determine homogenized cross sections and discontinuity factors for rodded nodes and nodes adjacent to the core reflector interface, predictions of node-averaged powers again match fine-mesh reference results to within 1%. Use of color sets for BWR's has not yet been studied.

For the case of a highly accurate nodal code such as QUANDRY, the discontinuity factors take care primarily of errors due to homogenization procedures. They can, however, be used to reduce errors from many other sources. We are currently studying their use is three areas:

(a) To reduce the number of energy groups needed for accurate fast and thermal reactor calculations.

(b) To simplify the structure of the QUANDRY equations and thereby reduce computer storage requirements (a spinoff will be to derive all the conventional nodal equations - FLARE, SIMULATE, EPRI-NODE, etc. - systematically from the QUANDRY equations).

(c) To solve transport problems using equations of group-diffusion finite difference form.

It is possible to define "exact" discontinuity factors so that all of these goals can be achieved without any error. However, again, the exact solution is required a priori to find these "exact" factors. The heart of the problem is then to find simple ways of obtaining accurate approximations to the exact values. Preliminary results have been encouraging.

(3) Dehomogenization

Several methods have been developed for reconstructing detailed heterogeneous flux shapes from node-averaged values. These are all based on the fact that node-face-averaged fluxes and currents for the heterogeneous reactor can be backed out of a QUANDRY solution, and this information can be used by interpolation to infer node-corner-point flux values. The reconstructed flux for a given group is then expressed as the product of a detailed two-dimensional "assembly shape" (obtained from a heterogeneous, finite-difference assembly or color set calculation) multiplied by a triquadratic "form function" (a 27-term expression having terms of the form $a_{ijk}\ x^i\ y^j\ z^k$, $i, j, k = 0, 1, 2$). The $a_{ijk}$ are found by fitting to the QUANDRY output. For simple two- and three-dimensional PWR benchmark problems the method predicts values for hot-pin powers as calculated by fine mesh finite-difference techniques to within 1%. For the two-dimensional case, the calculation was run through the beginning of a third fuel cycle. The agreement within 1% for power in the hot pins persisted. The error of 1% holds for all fuel pins (high and low powered) except those close to the radial core-reflector interface. There is 3.5%, except on the top and bottom planes of the core where it is as much as 7.5%.

(4) Nodal Kinetics

QUANDRY was originally developed as a transient code. Its transient capability has now been extended by combining it with the thermal-hydraulic code THERMIT to form a composit called TITAN (See Section 3.2.9), one of the most sophisticated tools available for analysing three-dimensional power transients within an LWR core.

The use of QUANDRY for transient analysis increases the importance of two refinements which we have been studying for some time. The first of these relates to representing the effect of reflectors by using albedoe boundary conditions at the core reflector interface (thereby saving running time). It is possible to use discontinuity factors to make that representation error-free provided a reference quarter core solution is available. But we have been unable to find a reliable, cheap way to determine accurate albedoe boundary conditions employing only local calculations. Instead, we have had to move a quarter of an assembly distance out into the reflector and there apply one- and two-dimensional analytic formulas to compute albedoes. This procedure seems to be quite accurate. However, it saves only 10 - 20% of the computer running time (over that required if the entire reflector is represented explicitly) rather than the 20 - 30% that would be saved if the entire reflector could be replaced.

The second refinement is more important. It deals with the resolution of the so-called "control rod cusping problem". This is a phenomenon which occurs when the withdrawal of a control rod from a large node is represented nuclearly by a homogeneous absorption cross section throughout the node proportional to the fraction of the axial length of the node occupied by control rod material. Representing the rod behavior in this way leads to unphysical cusps in the curve of reactivity vs control rod position. Nodal power distributions also exhibit errors.

By representing a partially inserted rod as homogenized in the radial plane of the node but as a two-region absorber in the axial direction, by then finding a homogenized, flux-weighted cross section over the axial length of the node and then by computing axial discontinuity factors for the node in order to correct for deficiencies in this flux-weighting procedure, we have been able to eliminate the cusping problem almost entirely. Moreover the axial flux shapes and node-face-currents needed for the axial spatial weighting and discontinuity factors can be generated entirely within the framework of the QUANDRY model. No special pre-computations or interpolating tables are needed.

Nodal Point Kinetics

The point kinetics equations provide a very cheap way to predict transient behavior for situations in which the spatial shape of the flux (as opposed to its magnitude) changes very little. These equations are driven by the global reactivity of the reactor, and that quantity in turn is calculated by a perturbation theory expression.

The usual perturbation theory expression involves terms in the gradient of the flux and the gradient of the adjoint flux. But these gradients are not available from a nodal solution. Rather than ignore the terms (as is often done), we have derived a perturbation formula directly from the matrix equations that express the QUANDRY model. Unfortunately the resultant expressions for the point kinetics parameters involve the solution of the steady state adjoint QUANDRY equations, and creating a code to solve these equations turns out to be very difficult.

As an interim approximation we have made use of discontinuity factors to cast QUANDRY into its equivalent finite difference form and then created a code to find the solution of the adjoint of these much simpler equations. Values of the parameters needed for the point kinetics equations are then computed from the reduced finite difference form of the QUANDRY regular and adjoint equations. The procedure is not exact since the discontinuity factors needed to reduce the regular QUANDRY equations to finite difference form are not the same as those required to reduce the corresponding adjoint equations. The errors which arise from neglecting the difference are currently being assessed. They appear to be small.

Investigators: Professor A.F. Henry; Messrs. M-H Chang, P.J. Finck, R. Gamino, B. Hagemeier, C.L. Hoxie, H-S Joo, H. Khalil, I. Muhtaseb, D.K. Parsons, J. Perez, T. Taiwo, and F.A. Yarman.

Support: Electric Power Research, MIT Energy Laboratory Utility Program, Nuclear Utilities Services, Studsvik of America, Inc.

Related Academic Subjects:

| | |
|---|---|
| 22.211 | Nuclear Reactor Physics I |
| 22.212 | Nuclear Reactor Physics II |
| 22.213 | Nuclear Reactor Physics III |
| 22.42 | Numerical Methods in Engineering Analysis |
| 22.43 | Advanced Numerical Methods in Engineering Analysis |

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M. Khalil, "The Application of Nodal Methods to PWR Analysis," Ph.D. Thesis, Department of Nuclear Engineering, MIT, December 1982.

H. S. Khalil, P.J. Finck, and A. F. Henry, Reconstruction of Fuel Pin Powers from Nodal Results, Proceedings of a Topical Meeting, Advances in Reactor Computations, Salt Lake City, March 28-31, 1983, ANS Idaho Section, ISBN: 0.89448-111-8, p. 367.

C.L. Hoxie and A. F. Henry, "Reconstruction of Heterogeneous PWR Flux Shapes from Nodal Calculations," Trans. Amer. Nucl. Society Vol. 39, p. 905, November 1981.

### 3.1.3 Fast Reactor Physics and Core Design

Work completed in August 1983 on a major research effort - the MIT Fast Reactor Blanket Project - which was initiated in 1967, and which over the years supported more than 40 students as research assistants; 19 completed doctoral theses on the project, while 23, 3 and 4 carried out master's, engineer's and bachelor's thesis projects, respectively. In addition, another 31 students were associated to a lesser extent - carrying out special project research for subject credit, working part-time as lab assistants, etc.

During this span of time, work was carried out on a wide range of subtasks, ranging from neutronic and photonic measurements in mockups of blankets using the Blanket Test Facility at the MIT Research Reactor, to analytical/numerical investigations of blanket design and economics.

Investigators: Professors M.J. Driscoll, D.D. Lanning and A.F. Henry; Computer Operations Assistant, R. Morton; Messrs. A. Wolford, F. Yarman.

Support: U.S. Department of Energy (terminated).

Related Academic Subjects:

| | |
|---|---|
| 22.212 | Nuclear Reactor Physics II |
| 22.213 | Nuclear Reactor Physics III |
| 22.35 | Nuclear Fuel Management |

Recent References:

M.J. Driscoll, "MIT LMFBR Blanket Research Project, Final Summary Report", DOE/ET/37241-54, MITNE-257, August 1983.

### 3.1.4 LWR Uranium Utilization Improvement

A major series of research projects in this area, carried out for the DOE, which commenced in May 1976, were completed in August 1982. A total of eight doctoral theses, thirteen master's or engineer's theses, and one bachelor's thesis, were completed under this program.

Work continues in the following major areas: methods development for the automated identification and evaluation of candidate PWR reload arrangements, including optimum selection of burnable poison loadings; and a program to determine optimum intermediate and long-range strategy for all key transactions and design/operating decisions in the LWR fuel cycle.

Much of this work has been based on extensions of the linear reactivity method of reactor core behavior. The work at MIT has been sufficiently broad in scope and successful that a technical monograph is being prepared on this subject.

Investigators: Professors M. J. Driscoll and D.D. Lanning; Messrs. T. J. Downar, I.L.Sauer, M.A. Malik, M.G.Izenson, E. Montaldo-Volachec, A. Kamal, W. T. Loh, M. W. Zimmermann, D. W. Charpie, and R. L. Coxe.

Support: U.S. Department of Energy via MIT Energy Laboratory (terminated); Westinghouse Electric Corporation.

Related Academic Subjects:

| | |
|---|---|
| 22.212 | Nuclear Reactor Physics II |
| 22.213 | Nuclear Reactor Physics III |
| 22.35 | Nuclear Fuel Management |

Recent References:

P.E. Cavoulacos and M.J. Driscoll, "Probabilistic Analysis of Nuclear Fuel Cycle Economics", Proc. ANS Topical Meeting on Technical Bases for Nuclear Fuel Cycle Policy, Newport, R.I., September 1981.

M.J. Driscoll, "Methods for the Evaluation of Improved PWR Core Design", Proc. ANS Topical Meeting on Technical Bases for Nuclear Fuel Cycle Policy, Newport, R.I., September 1981.

A. Kamal, M.J. Driscoll and D.D. Lanning, "The Selective Use of Thorium in PWR's on the Once-Through Fuel Cycle", Trans. Am. Nucl. Soc., Vol. 39, November 1981.

M. A. Malik, A. Kamal, M.J. Driscoll, and D. D. Lanning, "Optimization of the Axial Power Shape in Pressurized Water Reactors", DOE/ET/34022-2, MIT-EL-81-037, November 1981. (S.M. Thesis by M.A. Malik.)

W. T. Loh, M.J. Driscoll and D. D. Lanning, "The Use of Burnable Poison to Improve Uranium Utilization in PWR's", DOE/ET/34022-3, MIT-EL-82-014, May 1982. (Ph.D. Thesis by W. T. Loh.)

A. Kamal, M. J. Driscoll and D. D. Lanning, "The Selective Use of Thorium and Heterogeneity in Uranium-Efficient Pressurized Water Reactors", DOE/ET/34022-4, MIT-EL-82-033, August 1982. (Ph.D. Thesis by A. Kamal.)

M.J. Driscoll, "Final Report on Improved Uranium Utilization in PWRs", MIT-EL-82-032, August 1982.

M.J. Driscoll, "A Review of Thorium Fuel Cycle Work at MIT", invited paper, US-Japan Joint Seminar on the Thorium Fuel Cycle, Nara, Japan, October 1982.

D.W. Charpie, "Cost/Benefit Analysis of Stockpiling in the Nuclear Fuel Cycle", S.M. Thesis, Department of Nuclear Engineering, MIT, May 1983.

M.G. Izenson, "Automated PWR Reload Design Optimization", SM Thesis, Department of Nuclear Engineering, MIT, June 1983.

M.W. Zimmermann, "A Critique and Simplification of Fuel Cycle Economics Calculations", SM Thesis, Department of Nuclear Engineering, MIT, August 1983.

R. L. Coxe, "The Economic Optimization of Uranium Enrichment Tails Assays", S.B. Thesis, Department of Nuclear Engineering, MIT, June 1982.

## 3.2 Reactor Engineering

Because of the important and expanding role of nuclear power reactors in central station electric power generation, the Department gives major attention to teaching and research in a broad spectrum of reactor engineering fields, including reactor thermal analysis, power reactor safety, nuclear reactor and energy system design, nuclear fuel and power system management, fuel designs for plutonium recycle and reactor dynamics.

### 3.2.1 Subjects of Instruction

A total of eighteen subjects of instruction are offered under the category of reactor engineering by the Department. The following paragraphs present a description of all of the subjects in reactor engineering.

22.03: Engineering Design of Nuclear Power Systems, is an undergraduate offering which introduces nuclear engineering principles to analyze the system design of current U.S. central station power reactors. Topics covered include: the elementary economic aspects of electric power generation; heat generation, transfer, and transport; radiation protection and safety analysis.

22.031: Engineering of Nuclear Reactors, topics covered include power plant thermodynamics, reactor heat generation and removal (single-phase as well as two-phase coolant flow and heat transfer) and structural mechanics. Engineering considerations in reactor design. Lectures are in common with 22.312, but assignments differ.

22.033: Nuclear Systems Design Project, is a group design project involving integration of reactor physics, control, heat transfer, safety, materials, power production, fuel cycle management, environmental impact, and economic optimization. The subject provides the student with the opportunity to synthesize knowledge acquired in other subjects and apply this knowledge to practical problems of interest in the reactor design field. The subject meets concurrently with 22.33, but assignments differ.

22.05: Introduction to Engineering Economics, introduces methods used by engineers for the economic analyses of alternatives. Topics covered include time-value-of-money mechanics; present worth and rate-of-return methodology; dealing with depreciation and taxes, inflation, and escalation; levelized cost; replacement and retirement problems. Also, component cost modeling, economy-of-scale and learning-curve effects, cost-risk-benefit analysis, insurance, and other probabilistic applications are presented.

22.311: Energy Engineering Principles, is intended primarily for students who did their undergraduate work in physics or other fields which did not provide much instruction in engineering principles. Topics dealt with include fundamentals of engineering thermodynamics, fluid flow, heat transfer, and elasticity, with examples of applications to various energy sources.

22.312: Engineering of Nuclear Reactors, covers engineering principles of nuclear reactors emphasizing applications in central station power reactors. Power plant thermodynamics; energy distribution and transport by conduction and convection of incompressible one- and two-phase fluid flow in reactor cores; mechanical analysis and design.

22.313: Advanced Engineering of Nuclear Reactors, emphasizes thermo-fluid dynamic design methods and criteria for thermal limits of various reactor types. Topics treated include fundamentals of transient heat transfer and fluid flow under operational and accidental conditions. Detailed analysis of fluid flow and heat transfer in complex geometries.

22.314J: Structural Mechanics in Nuclear Power Technology, deals with techniques for structural analysis of nuclear plant components. It is a joint subject with five other engineering departments (Civil, Mechanical, Materials, Ocean, and Aero/Astro) since nuclear plant components illustrate applications of these disciplines. The structural aspects of plant components are discussed in terms of functional purposes and operating conditions (mechanical, thermal, and radiation). A designer's view is adopted, emphasizing physical rationale for design criteria and methods for executing practical calculations. Application topics include fuel performance analysis, reactor vessel safety, flow induced vibrations, and seismic effects.

22.32: Nuclear Power Reactors, is a descriptive survey of engineering and physics aspects of current nuclear power reactors. Design details are discussed including requirements for safety of light and heavy water reactors, high temperature gas-cooled reactors, fast reactors both liquid-metal and gas-cooled, and fast breeder reactors. Reactor characteristics are compared both in class and by individual student projects. Development problems are discussed and potentials for future improvements are assessed.

22.33: Nuclear Engineering Design, is a group design project involving integration of reactor physics, control, heat transfer, safety, materials, power production, fuel cycle management, environmental impact, and economic optimization The subject provides the student with the opportunity to synthesize knowledge acquired in other subjects and apply this knowledge to practical problems of interest in the reactor design field. The subject meets concurrently with 22.033, but assignments differ.

22.341: Nuclear Energy Economics and Policy Analysis, presents a comprehensive assessment of the economic, environmental, political, and social aspects of nuclear power generation and the nuclear fuel cycle. Quantitative applications of the principles of engineering economics; comparison of alternatives using discounted cash flow methods. Technology assessment/policy analysis of institutional alternatives for R&D, management, and regulation; includes nuclear power plant licensing, nuclear waste management, and nuclear power and weapons proliferation.

22.35: Nuclear Fuel Management, prepares students for work in the area of nuclear fuel economics and management. Characterizes the space-time history of nuclear fuels and the effects upon fuel costs. Topics covered include physical and material constraints upon fuels and their effects on fuel management policies; methods of analysis for the optimization of fuel costs; and a qualitative description of current methods of management and areas of future development.

22.36J: Two-Phase Flow and Boiling Heat Transfer, is a specialized course in the power reactor engineering curriculum offered in conjunction with the Mechanical Engineering Department. Topics treated include phase change in bulk stagnant systems, kinematics and dynamics of adiabatic two-phase flow, with boiling and/or evaporation, thermal and hydrodynamic stability of two-phase flows and associated topics such as condensation and atomization. Both water and liquid metal applications are considered under each topic where data exists.

22.37: Environmental Impacts of Electricity, assesses the various environmental impacts of producing thermal and electric power with currently available technology. Compares impacts throughout both the fossil and nuclear fuel cycles. Topics include fuel resources and extraction, power station effluents, waste heat disposal, reactor safety, and radioactive waste disposal.

22.38: Reliability Analysis Methods, covers the methods of reliability analyses including fault trees, decision trees, and reliability block diagrams. Discusses the techniques for developing logic diagrams for reliability assessment, the mathematical techniques for analyzing them, and statistical analysis of required experience data. Practical examples of their application to the risk assessment of nuclear power reactors and other industrial operations are discussed.

22.39: Nuclear Reactor Operations and Safety, deals with the principles of operating nuclear reactor systems in a safe and effective manner. Emphasizes light water reactor systems with transient response studies including degraded core recognition and mitigation. Other topics include:

consequence analysis and risk assessment; lessons from past accident experience; NRC licensing and regulations. Demonstrations include operation of the MIT Research Reactor and the use of a PWR concept simulator. An optional lab section is available.

22.40J: Advanced Reliability Analysis and Risk Assessment, deals with the extended application and use of reliability and probabilistic risk analysis methods. Methods for common mode failure analysis and treatment of dependencies are covered. Other areas discussed are Bayesian statistics applied to reactor safety problems, error sensitivity analysis, and the application of selected reliability analysis computer codes. Case studies of safety analyses performed in nuclear and non-nuclear areas.

22.43: Advanced Numerical Methods in Engineering Analysis, covers advanced computational methods used in analysis of nuclear reactor engineering problem studies. Emphasizes the solution of multi-dimensional problems and non-linear equations using modern iterative techniques. Topics include finite difference and finite elements formulations with applications to incompressible and compressible flows. Introduction to numerical turbulence modeling. Additional special topics covered depending on the interests of the class.

Most undergraduate students in the Department take 22.03, 22.031, and 22.033, and most graduate students take 22.311 or 22.312. Those whose special interests lie in the general area of reactor engineering or related areas, take various choices from the advanced engineering subjects.

### 3.2.2 Flow Distribution and Heat Convection in Rod Bundles

An experimental and analytical program has been continuing at MIT on investigation of flow distribution and heat convection mechanisms in bare and wire-wrapped bundles. The effort in this program has been split among the three major flow and heat transfer regimes: forced convection, mixed convection and flow recirculation.

In the forced convection area, refined bundle and subchannel averaged friction factor and flow distribution models are developed, based on an extensive list of world's data recently compiled here. The emphasis now has shifted towards flow resistance modeling on a more local scale, pertinent to the scale of subchannel analysis and porous body type of numerical programs. The discretization of the integral conservation equations on the numerical control volumes of these methods is reconsidered and new formulations of the pressure, convective and flow resistance terms of the momentum equations are being developed.

In the mixed convection area work is concentrated on the fundamental characteristics of such flows in rod bundles. Using dimensionless analysis and semi-theoretical expressions, the effects of the flow rate, input power, power distribution profile, bundle geometrical characteristics and fluid properties on friction factor and heat transfer coefficient experimental data are being analyzed. Simple isolated channel mathematical models are developed in order to analyze global flow distribution effects and onset of flow recirculation. Also conduction and turbulence mixing models for heat transport under thermal plums (which characterize the mixed convection regime) are developed.

Finally, in the flow recirculation area emphasis is placed on improving our understanding of the causes of flow recirculation, the phenomenology (or topology) of the recirculation flow patterns and the stability of this regime (stable, steady but unstable, periodic, unsteady). In particular, under sufficiently low flow conditions, flow recirculation which can cause undesirable temperature excursions is more likely to occur in geometries with large power skews. In order to assess this possibility of temperature excursion, experimental observations and computer simulations will be performed on blanket geometry to supplement the phenomenological model approach.

1. Forced Convection Area - Lead length averaged and local formulations for thermal and hydraulic parameters - Recent accomplishments here have been:

(a) Development of hydraulic resistance models for porous body or wire-wrapped rod bundles, including

Development of the ASFREMIT subchannel analysis code which includes the above resistance models.

Adoption of the hydraulic resistance models to the THERMIT porous body type code.

(b) Establishment of a Hot-Film Anemometry technique to obtain flow splits for low Reynolds flows in the MIT wire-wrapped bundle and development of flow split correlations.

(c) Development of mixing parameter correlations in forced convection.

2. Mixed Convection Area - Recent accomplishments have been:

(a) Formulation of the non-dimensional differential conservation equations and their boundary conditions for vertical fully developed laminar flows in ducts.

(b) Establishment of a methodology to measure pressure drops in low Reynolds mixed convection flows in rod bundles.

(c) Acquisition of pressure drop and friction factor coefficient data under mixed convection and recirculation flow conditions in both the MIT bare and wire-wrapped bundles.

(d) Design and construction of an instrumented rod to measure wall temperatures of a heated rod. Application of this rod to obtain mixed convection Nusselt number data in the wire-wrapped bundle.

(e) Development of a correlation for turbulent mixing under low Reynolds, mixed convection conditions.

(f) Development of a criterion for onset of mixed convection.

3. Flow Recirculation Area - Recent accomplishments have been:

(a) Development of a criterion of onset of recirculation based on a two-channel model. The result was presented in a flow regime map so that a simple calculation is able to locate an operating point for a given power skew and flow rate.

(b) Testing of the flow recirculation criterion by employing COBRA computational results and the 4x4 square array tests.

(c) Completion of detailed temperature profile measurements for the 4x4 bare rod bundle operating from forced to mixed and finally into the recirculation flow regime. A concept of "flow recirculation length" was introduced from the temperature profiles analysis.

Investigators: Professors N.E. Todreas and W.M. Rohsenow (Mechanical Engineering); Messrs. A. Efthimiadis, S.K. Cheng, T.T. Huang, T. Okada, T.S. Ro and K. Suh.

Support: Department of Energy, Power Reactor Development Corporation (Japan), Westinghouse.

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer

References:

Efthimiadis, A. and Todreas, N.E., "Mixed Convection and Hydrodynamic Modeling of Flows in Rod Bundles," Report No. PNC/MIT-11TR, Massachusetts Institute of Technology, May 1984.

Cheng, S.K. and Todreas, N.E., "Constitutive Correlations for Wire-Wrapped Subchannel Analysis under Forced and Mixed Convection Conditions," Report No. DOE/ET/37240-107TR, Massachusetts Institute of Technology, to be issued August 1984.

Todreas, N.E., Efthimiadis, A., Okada, T., Ro, T.S., Suh, K.Y., "Mixed Convection Testing and Analysis of Wire-Wrapped Bundles," Progress Report No. PNC/MIT-10, Massachusetts Institute of Technology, June 1984.

Todreas, N.E., Efthimiadis, A., Okada, T., Ro, T.S., Suh, K.Y., "Mixed Convection Testing and Analysis of Wire-Wrapped Bundles," Progress Report No. PNC/MIT-12, Massachusetts Institute of Technology, to be issued August 1984.

Symolon, P.D., Todreas, N.E. and Rohsenow, W.M., "Criteria for the Onset of Mixed Convection and Onset of Recirculation in Vertical Rod Bundles," Report No. DOE/ET/37240-101TR, Massachusetts Institute of Technology, November 1983.

Todreas, N.E., Huang, T.T., "Prediction of Temperature and Velocity Fields in Wire-Wrapped Rod Arrays," Progress Report No. 2, Westinghouse Electric Corporation Contract No. 54-7-CAR-319570-94311, Massachusetts Institute of Technology, May 1984.

Huang, T.T., Todreas, N.E., "Application of the MIT Two-Channel Model to Predict Flow Recirculation in Ward 61-Pin Blanket Tests," Report No. DOE/ET/37240-104TR, Massachusetts Institute of Technology, January 1983.

Okada, T. and Todreas, N.E., "Mixed Low Reynolds Convection Pressure Drop, Velocity and Temperature Measurements in a 19-Pin Wire-Wrapped Bundle," Topical Report, Report No. PNC/MIT-13TR, Massachusetts Institute of Technology, to be issued September 1984.

### 3.2.3 Theoretical Determination of Local Temperature Fields in LMFBR Fuel Rod Bundle

Helical wire wraps are widely used in fast reactor fuel and blanket assemblies to enhance coolant mixing and to maintain proper spacing between fuel pins. However, the presence of a helical wire may possibly induce other heat transfer problems such as an increase of maximum surface clad temperature. Such a temperature increase is very important to reactor designers because they must assure that thermal safety margins are always met. To accurately predict the clad temperature increase induced by the helical wire, a local subchannel heat transfer analysis is necessary.

In this study, we will restrict our attention to an interior local subchannel with a fuel pin located at the center. Within this region of interest, the thermal-hydraulic behavior of the fluid will be strongly dependent on the location of the helical wire of the center pin and also the wires of the neighboring pins. To minimize the non-uniform boundary condition in the problem, a rotating coordinate transformation is performed such that the wire of the center pin will be stationary at a fixed angle in the new system. This transformation would, however, lead to a complicated representation of the wires of the neighboring pins. Because the effect of the wires of the neighboring pins is secondary, the simpler approach of representing these wires as a set of discrete flow blockages is adopted.

In this analysis, the governing equations are the three basic laws of mass, momentum and energy conservation for a single phase, incompressible, transient, three-dimensional flow. Neither heat transfer correlations, friction factor correlations nor empirical mixing functions will be used. This set of governing equations will be solved numerically by the DICE technique.

Although our analysis is mainly on the local subchannel, we do account for the fluid interaction with the neighboring subchannel by imposing a physical boundary condition on the outside boundary. Unlike the isolated boundary condition, a physical boundary condition implies that the outside boundary condition allows both crossflow and heat transfer which can be derived either from the available experimental data or from the results of the lumped parameter subchannel analysis. In the present calculation, we utilize the velocity data from the Westinghouse Isothermal Air Flow Experiments to establish the outside boundary condition. To study the subchannels interaction effect, both the isolated and physical boundary conditions have been analyzed. Velocity field as well as the friction factor of the physical boundary condition show that our results compare well with the WARD experiments. We also study the heat transfer characteristics of the CRBR fuel and blanket assemblies. For the fuel assembly, an increase of the maximum clad temperature by 10° Kelvin is observed when the wire is in contact with the neighboring pins. However, for the blanket assembly, a smaller increase of the maximum clad temperature is predicted because of a lower heat generation rate.

Investigators: Professors N. Todreas and L. Wolf; Mr. C.C. Wong.

Support: U.S. Department of Energy

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors
22.33 Nuclear Engineering Design
22.42 Numerical Methods in Engineering Analysis
22.43 Advanced Numerical Methods in Engineering Analysis

Recent References:

C.C. Wong and N.E. Todreas, "Wire-Wrapped Rod Bundle Heat Transfer Analysis for LMFBR," DOE/MIT Report DOE/ET-37240-97TR (Oct. 1981).

C.C. Wong and N.E. Todreas, "Local Heat Transfer Analysis of LMFBR Wire-Wrapped Rod Bundle," Proceeding of International Conference on Numerical Methods in Nuclear Engineering in Montreal, Canada, Part 2, p.806-828, (Sept. 1983).

C.C. Wong and N.E. Todreas, "Wire-Wrapped Rod Bundle Heat Transfer Analysis for LMFBR," Transactions of ANS 1983 Winter Meeting in San Francisco, Vol. 45, P.823-825, (Nov. 1983).

C.C. Wong and N.E. Todreas, "Wire-Wrapped Rod Bundle Heat Transfer Analysis for LMFBR," 1st Proceeding of Nuclear Thermal Hydraulic Division of the American Nuclear Society, P. 36-43,(Nov. 1983).

### 3.2.4 PWR Steam Generators

Recent trends in plant safety analysis have revealed a need for benchmark analytical representations of the steam generators to aid in the improvement of system codes and of fast codes for operator assistance. A model for such applications should exhibit four characteristics. First, it should be capable of responding to actual system boundary conditions. Second, it should be based on detailed physical models, supplemented by well-tested empirical correlations and utilize a reliable numerical method while still allowing for the assessment of potentially simplifying assumptions. Third, it should be validated. Fourth, it should provide a basic framework for expansion to severe transient analysis.

A model satisfying these characteristics has been developed. The downcomer, evaporator and riser are treated by the two-fluid, three-dimensional code THERMIT. A zero-dimensional calculation closes the natural circulation loop by linking the riser to the downcomer. Effects included are: condensation, flashing, structure and liquid heat sinks and compressibility in the steam dome. The primary-side representation allows for any number of tubes per secondary-role computational cell. For each tube, four temperatures are calculated: primary fluid, primary wall, intermediate wall and secondary wall.

The capability for calculating parameter distributions with coarse resolution at full and half power has been verified. Results are in excellent agreement with measurements conducted at the Westinghouse Model Boiler No. 2, as well as with calculations by the ATHOS code. Global parameter computations for both mild and severe operational transients have also been verified. Calculations compare well with plant start-up data gathered at the Arkansas Nuclear One Unit-2 facility.

A current application of this work is in the study of steam generator primary tube rupture incidents. Preliminary talks with both the NRC and the Los Alamos National Laboratory indicate that there is great interest in some of these studies which can be done with the present code.

Investigators: Professors N.E. Todreas, D.D. Lanning, and J.E. Meyer; Messrs. H.C. daSilva, Jr., and Y. Khalil (for the code development) and Professor Andrei Schor (for tube rupture studies).

Support: Northeast Utilities Service Co. and Yankee Atomic Electric Co. for the code development. Los Alamos National Laboratory for the tube rupture studies.

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors
22.363 Two-Phase Flow and Boiling Heat Transfer
22.43 Advanced Numerical Methods in Engineering Analysis

Recent Publications:

H.C. daSilva, Jr., "Thermohydraulic Analysis of U-Tube Steam Generators," Ph.D. Thesis, Department of Nuclear Engineering, MIT, February 1984.

### 3.2.5 Mixed Convection in Multiple Parallel Channels Connected Only at Plena

Liquid metal reactor (LMR) systems are currently being investigated to evaluate their behavior under conditions of decay heat removal. Under these conditions, mixed convection exists through the core since the flow rates are low and thus the buoyancy term in the momentum equation is significant. The energy and momentum equations must therefore be solved in a coupled manner. In current LMR designs, assemblies are enclosed and thus the vessel can be modeled as a system of parallel channels connected only at the top and bottom plena.

Under forced convection conditions, the interassembly flow distribution is controlled by the designed orificing scheme. As the flow regime in the assemblies change from forced to mixed convection, the flow distribution will change. In general, assemblies with higher power would be expected to draw more flow because of the greater temperature rise and the associated density reduction. If the flow entering and leaving the vessel is very low, it is possible that the flow in the low power assemblies will either stagnate or reverse directions, leading to high clad and/or coolant temperatures. In order to evaluate safety margins for core cooling, accurate flow distribution models are necessary.

At General Electric, decay heat removal in LMRs was investigated with a water model test loop consisting of six parallel-annular flow channels representing various core assemblies plus a return and a bypass channel. The MIT work will focus on developing a physical understanding and analytic/numerical prediction of experimental results from this model. In addition, recent GE tests on scaled vessel experiments will be reviewed and specific hydrodynamic correlations for rod bundle regions will be suggested. These correlations will be from existing literature and from recent MIT test results and could be used in 3-D codes currently being used in scaled vessel analyses.

In order to numerically predict the GE parallel channel test results, a computer code called MICG was written. MICG solves the 1-D conservation equations for an incompressible liquid flowing in parallel channels. Integration techniques included for user selection and the box method, Turner's method, and the method of characteristics. In addition, models for heat conduction and heat transfer to account for heat losses from the coolant channels to the environment are included. Coolant temperatures and pressures in the plena can be either calculated assuming a uniform profile or input by the user.

In parallel with this numeric work a small, two-channel experiment is being conducted. This experiment will help in determining the stability of mixed convection in parallel channels, the conditions leading to flow stagnation in a heated channel, intra-channel flow recirculation patterns during flow stagnation; flow recirculation patterns at the channel exit; and the effect of flow orificing on peak channel temperatures.

Investigators: Professor N. Todreas, Dr. S. Kaizerman, Mr. V. Iannello

Support: General Electric.

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer

Recent References:

S. Kaizerman and N.E. Todreas, "Mixed Convection in Multiple Parallel Channels Connected at Plena," Report No. GE/MIT-1, Massachusetts Institute of Technology, March 1983.

S. Kaizerman, V. Iannello, and N.E. Todreas, "Mixed Convection in Multiple Parallel Channels Connected at Plena," Report No. GE/MIT-2, Massachusetts Institute of Technology, May 1984.

### 3.2.6 Fluid Dynamic Modeling of Forced-Buoyant Flow in Reactor Vessel Plenums

Analytical and experimental work is being pursued with the goal of improving understanding of, and models for, behavior of turbulent mixing of buoyant flows. The specific problem examined concerns development of models for flow mixing in the LMFBR outlet plenum. To do this the influence of different turbulence models upon predicted mixing patterns are being investigated. These results are to be compared to measured velocity and temperature fields, and measured velocity and temperature correlations functions, with the aim of developing an appropriate turbulence model for use in design calculations. In a broader sense this work permits an investigation into the nature of turbulent mixing in buoyant flows, which has application in a wide range of practical problems.

In recent work it has been seen for many important reactor design problems that truncation error effects (inherent in numerical simulation methods) can be of equal magnitude to important physical transport phenomena. This can lead to flawed design analyses.

In an effort to improve upon this situation an examination of alternative numerical treatments of fluid flow problems has been performed in order to identify and improve upon methods providing low error, stable predictions.

Current work is concerned with turbulence in three-dimensional highly anisotropic flows.

Investigators: Professor M.W. Golay and Mr. R. Sawdye.

Support: None.

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors
22.43 Advanced Numerical Methods in Engineering Analysis

Recent References:

D.R. Boyle and M.W. Golay, "Measurement of a Recirculating, Turbulent Flow and Comparison to Turbulence Model Predictions. I: Steady State Case," J. Fluids Engineering, 105, 439-446 (1983).

D.R. Boyle and M.W. Golay, "Measurement of a Recirculating, Two Dimensional Turbulent Flow and Comparison to Turbulence Model Predictions. II: Transient Case," J. Fluids Engineering, 105, 447-454 (1983).

### 3.2.7 Sodium Boiling in LMFBR Fuel Assemblies

The objective of this program is to contribute to the development of an improved understanding of sodium voiding behavior under postulated LMFBR accident conditions. The program consists of development of multidimensional computer models, capable of simulating low flow, low power conditions.

From among the possible two-phase flow models, two models were selected and have been pursued. The first uses a two-fluid (six-equation) representation, which needs more constitutive relations, but provides the potential for the broadest range of applications. The other uses a "mixture" (i.e., less than six-equation) description of the two-phase flow. In particular, a four-equation model is used, assuming thermal equilibrium on the saturation line between co-existing phases, but allowing for unequal phase velocities. This mixture model requires fewer constitutive relations, while still applicable to a wide range of conditions of interest.

Two codes have been developed based on the six-equation model: a two-dimensional code (NATOF-2D) and a three-dimensional code (THERMIT-6E). A three-dimensional code (THERMIT-4E) has been developed using the four-equation model.

The work has emphasized both the physical and the numerical modeling. A significant effort has been devoted to developing a consistent and realistic set of constitutive relationships for the six-equation model, including:

1. description of relative motion of the phases, via interphase momentum exchange and wall friction correlations,

2. flow boiling heat transfer models,

3. mass and heat interphase transfer rate models.

A consistent package of constitutive relations has also been assembled for the four-equation model. The code using this model has been used to test a number of modifications of the basic semi-implicit, non-linear solution scheme, aimed to take advantage of the reduction in the set of governing equations. A much improved understanding of some of the difficulties inherent to numerical modeling of sodium boiling has been gained.

The codes developed under this project have been verified by comparison to existing experimental results on sodium boiling. The results are very encouraging and indicate the general soundness of the approaches taken in this work. They have also helped in pointing those aspects of both physical and numerical nature that would be most likely to benefit from additional work.

Current work is focused on developing a loop simulation capability, emphasizing single- and two-phase natural circulation modeling, as a means of passive heat removal.

Investigators: Professors M. Kazimi, A. Schor, and N. Todreas; Messrs. O. Adekugbe, K.Y. Suh, H.C. No, and R. Zielinski.

Support: U.S. Department of Energy (October 1981 to March 1983).
Oak Ridge National Laboratory (since April 1983).

Related Academic Subjects:

22.36J Two-Phase Flow and Boiling Heat Transfer
22.43 Advanced Numerical Methods in Engineering Analysis

Recent References:

H.C. No and M.S. Kazimi, "The Effect of Virtual Mass on the Characteristics and the Numerical Stability in Two-Phase Flows," MIT-EL-81-023, (April 1981).

R.G. Zielinski and M.S. Kazimi, "Development of Models for the Two-Dimensional, Two-Fluid Code for Sodium Boiling NATOF-2D," MIT-EL-81-030, (September 1981).

K.Y. Suh and N.E. Todreas, "Simulation of Sodium Boiling Experiments with THERMIT Sodium Version," MIT-EL-82-023, (May 1982).

H.C. No and M.S. Kazimi, "Wall Heat Transfer Coefficient for Condensation and Boiling in Forced Convection of Sodium," Nucl. Sci. Eng., 81 (1982).

H.C. No and M.S. Kazimi, "Pressure Drop and Interface Drag Coefficient in Two-Phase Flow," Nuc. Sci. Eng., 82 (November 1982).

A.L. Schor and N.E. Todreas, "A Four-Equation Two-Phase Flow Model for Sodium Boiling Simulation of LMFBR Fuel Assemblies," Tenth Meeting of the Liquid Metal Boiling Working Group, Karlsruhe, Germany, (October 1982).

A.L. Schor and N.E. Todreas, "A Four-Equation Two-Phase Flow Model for Sodium Boiling Simulation of LMFBR Fuel Assemblies," MIT-EL-82-039, (December 1982).

A.L. Schor, M.S. Kazimi, N.E. Todreas, "Advances in Two-Phase Flow Modeling for LMFBR Applications," accepted for publication for the 2nd special issue

of Nuclear Engineering and Design on "LMFBR Two-Phase Rod Bundle Thermal-Hydraulics."

H.C. No and M.S. Kazimi, "An Investigation of the Physical and Numerical Foundations of Two-Fluid Representation of Sodium Boiling with Applications to LMFBR Experiments," MIT-EL-83-003, (March 1983).

### 3.2.8 Advanced Computational Methods for Single- and Two-Phase Flows

The objective of this work has been to study the application of the finite element method to the solution of the set of differential equations that describe the behavior of compressible and incompressible flow in one spatial dimension.

The direct application of the method to the set of differential equations, using the Galerkin's weighting and linear shape functions, gives generally unsatisfactory results for problems with steep spatial gradients. In order to improve the quality of the results, modifications have been made with respect to the treatment of some terms in the differential equations. The final formulation obtained is an accurate and stable numerical algorithm that converges very fast when solving gas or liquid single-phase problems. The scheme however encountered convergence difficulties when attempting to simulate problems characterized by extremely severe non-linearities such as boiling inception at low pressures.

Noteworthy the codes based on the method developed herein have been written in BASIC and implemented on 8-bit, 48K personal computer ATARI 800.

Alternative weighting schemes and non-linear solution techniques are currently being investigated.

Investigators: Professor A. Schor and Mr. J. Maldifassi-Pohlhammer

Related Academic Subjects:

22.36J Two-Phase Flow and Boiling Heat Transfer
22.43 Advanced Numerical Methods in Engineering Analysis

Recent References:

J. Maldifassi-Pohlhammer, "A Finite Element Method for Compressible and Incompressible Flow," S.M. Thesis, Nuclear Engineering Department, MIT, (August 1983).

Recent Publications:

B.W.Rhee, "Thermal Hydraulic Modeling of Pressurized Water Reactor Steam Generator," SM Thesis, Department of Nuclear Engineering, MIT, June 1981.

H. daSilva, "Thermohydraulic Analysis of U-Tube Steam Generators," Ph.D. Thesis, Department of Nuclear Engineering, MIT, February 1984.

### 3.2.9 Development of the Coupled Neutronic Thermal Hydraulic Code TITAN for LWR Applications

Modeling the behavior of a nuclear reactor core can be considered as consisting of two major parts: the thermohydraulic part and the neutronic part. In reality, the thermohydraulic behavior and the neutronic behavior are not always separable. The power level needed as input to the thermal codes, and the feedback parameters to calculate the neutronic behavior should ideally be calculated simultaneously. In practice, the situation is simplified in order to facilitate the calculations. The TITAN code is a code which has the ability to perform a three dimensional analysis of the complete core analysis (both thermohydraulic and neutronic parts). TITAN has been developed by combining two advanced codes previously developed at MIT, namely THERMIT and QUANDRY.

The THERMIT computer code is a 3-D, two-fluid, thermohydraulic code. In the two-fluid model two sets of partial differential conservation equations are solved for each individual fluid phase. The fluid dynamics model is a porous body model and can be applied to both core-wide or subchannel analyses. A complete heat transfer package is included which can determine appropriate regimes based on a complete boiling curve. The fuel rod radial heat transfer is solved by using temperature dependent properties. The rod can be divided into several rings, while the gap and the clad are assumed to consist of one ring each. The gap heat transfer coefficient can be assumed constant or variable. A semi-implicit numerical technique is used as a solution method. This method is not limited by the direction of the flow. However, the time step cannot exceed the time it takes the flow to cross a single node to insure stability. THERMIT is also designed to accept readily additional wall heat transfer models or constitutive inter-fluid models.

The QUANDRY computer code is a neutronics code based on a nodal method to solve space-dependent reactor transients. The two-group diffusion theory is utilized and the reactor is modeled as an array of homogenized regions (or nodes). In the nodal method, a one-dimensional diffusion equation for each direction is solved to yield the required neutron flux-current relationships. A quadratic polynomial approximation is used to calculate nodal transverse leakages. Considerable computational time is saved by this approach, relative to a finite difference method.

The coupling, in tandem, of QUANDRY and THERMIT has resulted in the computer code TITAN (Three Dimensional Integrated Thermal-hydraulic And Neutronic Code). In order to simplify the coupling logic, it was assumed that the same geometric model would be used for both neutronics and thermohydraulics calculations. The basic features that have been added to this code are:

1. Direct heating of the moderator
2. A restart capability
3. A unified input scheme
4. A linear and a non-linear feedback model.

Other features are being added as part of the present effort.

Code application to a sample problem which consisted of two adjacent part-length boiling water reactor fuel assemblies was carried out. The application involved a feedback sensitivity study, non-boiling and boiling steady-state cases and fuel pin model sensitivity studies. The results were reasonable and show that TITAN is correctly coupled, as can be seen from a comparison to QUANDRY and MEKIN for steady state, power profile. Transient analyses involving the two channel problem such as rod withdrawal and turbine trip have been performed. The calculational time observed was much more economic than MEKIN.

Also, a Brookhaven MEKIN-B code simulation of a PWR quarter core rod ejection problem was used as a calculational reference case. The TITAN results demonstrated very reasonable times for calculating such a large problem. They also demonstrated that the multi-dimensional nature of such a problem cannot be ignored.

Currently, an investigation of the sensitivity of TITAN to various neutronic and thermal hydraulic assumptions is being pursued. This includes assessment of the multi-dimensional effects of the neutronic models.

Investigators: Professors M.S. Kazimi and A.F. Henry; Messrs. D. Griggs, P. Kao and C. Tsai.

Support: Energy Laboratory Electric Utility Program.

Related Academic Subjects:

22.213 Nuclear Reactor Physics III
22.313 Advanced Engineering of Nuclear Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer

Recent References:

D.P. Griggs, A.F. Henry and M.S. Kazimi, "Development of a Three-Dimensional Two Fluid Code with Transient Neutronic Feedback for LWR Applications," MIT-EL-81-013 (1981).

D.P. Griggs, A.F. Henry and M.S. Kazimi, "Advanced Methods Development for LWR Transient Applications," MIT-EL-82-021 (1982).

D.P. Griggs, M.S. Kazimi and A.F. Henry, "TITAN: An Advanced Three Dimensional Neutronics Thermal-Hydraulics Code for LWR Safety Analysis," Proc. ANS Conf. on Advances in Reactor Physics and Core Thermalhydraulics, Kiamesha Lake, NY (1982).

S.P. Kao and M.S. Kazimi, "CHF Predictions in BWR Rod Bundles," Nuclear Technology, 60, 7-13, (Jan. 1983).

M.S. Kazimi and J.E. Kelly, "Formulation of a Two-Fluid Model for Mixing in BWR Bundles," Proc. 2nd Int'l Mtg. on Nuclear Reactor Thermal Hydraulics, Santa Barbara, CA (Jan. 1983).

C.K. Tsai, D.P. Griggs, M.S. Kazimi and A.F. Henry, "Development and Quarter Core PWR Rod Ejection Accident Application of the TITAN Code," MIT-EL 83-007, (June 1983).

3.2.10 Thermal Phenomena in LMFBR Safety Analysis

This program which started in 1977 aims at investigating the processes of thermal exchange between two fluids when either or both of them are in a liquid-vapor two-phase state. Such phenomena are of interest in analysis of fast reactor accidents. In particular, better definition of the interaction rate of two-component two-phase systems is needed in the computer models that describe the integral behavior of reactor materials under severe accident conditions.

The interaction processes of interest under accident conditions are those that can lead to significant early cooling of the molten fuel and hence decrease the potential for high mechanical energy release. The phenomena are studied by experimental and analytical models. The interaction modes of interest in this program can be divided into two categories:

1. In-Core Phenomena: This includes the rate at which heat can be transferred from molten fuel and/or vaporized fuel to the non-fuel components in the reactor core. In this regard the modes of heat transfer are those between fuel and steel within a molten pool as well as from the pool to the surrounding structures.

An investigation of the rate of pressurization of the molten core region for various assumptions was carried out. It was concluded that the heat transfer to the boundaries for the core region will control the rate of pressurization.

2. Out-of-Core Phenomena: This includes the rates of mixing and heat transfer from molten core materials to above core sodium in the vessel as the former is ejected into the latter following hypothetical meltdown conditions.

An experiment was conducted to ascertain the rate at which water is entrained in an expanding air jet. The effects of jet pressure and pool temperature were investigated. Higher entrainment was observed at lower jet pressures.

Investigators: Professors M.S. Kazimi, and W.M. Rohsenow; Ms. Joy Maneke.

Support: Nuclear Regulatory Commission (1978-1980).

Related Academic Subjects:

22.32 Nuclear Power Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer

Recent Publications:

R.A. Rothrock, M.S. Kazimi and W.M. Rohsenow, "Hydrodynamic Characteristics of a Gas Blowdown Into a Two-Dimensional Liquid Pool," Nucl. Eng. and Design, 71, 33-43, (1982).

R.C. Smith, W.M. Rohsenow and M.S. Kazimi, "Volumetric Heat Transfer Coefficients for Direct Contact Evaporation," J. Heat Transfer, 104, 163-170, (1982).

J.L. Maneke, "Thermodynamic Methods of Transition Core Pool Behavior following an LMFBR Hypothetical Accident," S.M. Thesis, Department of Nuclear Engineering, MIT, June 1983.

### 3.2.11 Application of Time Dependent Unavailability Analysis to Standby Safety Systems

The FRANTIC II computer code has been modified and used to demonstrate that time dependent unavailability analysis is a practical tool for assessing the periodic testing programs of operational standby safety systems.

FRANTIC II was assessed from an engineering point of view and modified as necessary to make it more useful for application to operational systems. An offset time was added to the component failure parameters to provide more flexible modeling of time dependent standby failures and the effects of test caused wear-out. A routine to calculate the optimum test interval of a constant failure rate component subject imperfect testing was also developed. The code was then coupled to a cutset generator and evaluator for application to multiple component systems. The resulting code is named FRANTIC II-MIT.

FRANTIC II-MIT has been applied to the High Pressure Coolant Injection System of a Boiling Water Reactor and a quantitatively based period testing program keyed to a fault tree evaluation of the system's safety functions has been formulated. The analysis indicated that system unavailability can be reduced while also reducing testing requirements from approximately 170 to 123 tests per year.

Investigators: Professor Norman C. Rasmussen, Dr. William E. Vesely, Jr.; Mr. Andrew A. Dykes.

Support: Brookhaven National Laboratory.

Related Academic Subjects:

22.38 Reliability Analysis Methods

Recent References:

A.A. Dykes, N.C. Rasmussen, W.E. Vesely, Jr., "Application of Time Dependent Unavailability Analysis to Standby Safety Systems," MITNE-251, (June 1982).

### 3.2.12 Economic Risks of Nuclear Power Reactor Accidents

Models to be used for analyses of economic risks from events which occur during U.S. LWR plant operation are developed in this study. The models include capabilities to estimate both onsite and offsite costs of LWR events ranging from routine plant forced outages to severe core-melt accidents resulting in large releases of radioactive material to the environment. The models have been developed for potential use by both the nuclear power industry and regulatory agencies in cost/benefit analyses for decision-making purposes.

The new onsite cost models estimate societal losses from power production cost increases, new plant capital costs, plant decontamination costs, and plant repair costs which may be incurred after LWR operational events. Early decommissioning costs, plant worker health impact costs, electric utility business costs, nuclear power industry costs, and litigation costs are also addressed.

The newly developed offsite economic consequence models estimate the costs of post-accident population protective measures and public health impacts. The costs of population evacuation and temporary relocation, agricultural product disposal, land and property decontamination, and land interdiction are included in the economic models for population protective measures. Costs of health impacts and medical care costs are also included in the models.

The newly developed economic consequence models are applied in an example to estimate the economic risks from operation of the Surry #2 plant. The analyses indicate that economic risks from LWR operation, in contrast to public health risks, are dominated by relatively high-frequency forced outage events. The implications of this conclusion for U.S. nuclear power plant operation and regulation are discussed. The sensitivities and uncertainties in economic risk estimates are also addressed.

Investigators: Professor N.C. Rasmussen, Dr. David Aldrich; Mr. Richard Burke.

Support: Sandia National Laboratory.

Related Academic Subjects:

22.40 Advanced Reliability Analysis and Risk Assessment.

Recent Reference:

R.P. Burke, "Economic Risks of Nuclear Power Reactor Accidents," Ph.D. thesis, Department of Nuclear Engineering, MIT, February 1984.

### 3.2.13 PBF Upper Plenum Fission Product and Aerosol Modeling

The Power Burst Facility (PBF) is currently planning a series of destructive tests of irradiated fuel. These experiments offer a unique opportunity to study the transport and deposition of fission products in these integral tests. Since many of the separate effects are not well understood, it will be difficult to interpret these integral experiments. Nevertheless, such a task needs to be done in order to make the PBF results more useful for addressing important safety issues, especially the severe accident source term.

It is proposed to conduct in-depth analysis to describe the fission product behavior in the SFD experiments. Special attention will be given to:

1. Aerosol formation and kinetics. How is the aerosol generated and what is the timing of fission product release relative to aerosol formation.

2. Fission product chemistry of Cs, I and Te. The chemical interactions of these fission products with control materials (Ag), cladding (Zr), structural material (Fe and Ni) and steam ($H_2O/H_2$ ratio) will be investigated in the core and upper plenum regions using thermodynamic calculations and, possibly, kinetic calculations.

3. Compatibility of analysis techniques and results with current computer models such as CORSOR and TRAP-MELT.

The result will be an analytic tool which could be used to help describe the behavior of fission products and aerosols in the PBF SFD 1-3 and 1-4 Tests. The analysis can then be compared with the results of the deposition measurements to identify the underlying physical mechanisms that control the aerosol and fission product behavior observed in these integral tests.

In order to conduct such analysis, it will be necessary to have fluid mechanical and thermal hydraulic information about the upper plenum. EG&G Idaho will perform thermal hydraulic analysis and supply the basic information needed on thermal hydraulic conditions. The analysis performed by MIT will assume this input data is available.

Investigators: Professor N.C. Rasmussen and Mr. David Petti

Support: Idaho National Engineering Laboratory.

Related Academic Subject:

22.40 Advanced Reliability Analysis and Risk Assessment.

Recent Reference: None to date.

3.2.14 Review of the Development of Safeguards Equipment by the U.S. Program for Technical Support to IAEA Safeguards (POTAS).

For approximately five years the U.S. has been contributing about $5 million/year in technical support to the International Atomic Energy Agency (IAEA) for the development of safeguards instrumentation. MIT was asked to review the POTAS program, including the equipment being developed and its rate of progress. Generally, what was found was that the program is producing a very good set of measuring instruments for a wide variety of safeguards measurements. Although the R & D part of the program was judged to be excellent, a shortcoming seemed to be that the rate of adoption of the new measuring techniques by inspectors in the field was slower than hoped for. The report discusses these issues and makes recommendations.

Investigators: Professor N.C. Rasmussen, Dr. Marvin Miller.

Support: Brookhaven National Laboratory.

Related Academic Subject:

22.76J Introduction to Nuclear Chemical Engineering.

### 3.2.15 The Safeguarding of Nuclear Facilities

This research consists of two tasks. The first task is to help develop analytical models in support of effects to devise efficient sabotage protection systems for nuclear facilities. So-called vital area analysis currently used in the design of such safeguards systems are based on studies of sabotage fault trees which are closely related to the fault trees used in the safety analysis of reactor systems as in WASH-1400. As presently used, the fault trees do not account for the inherent response times of the system to acts of sabotage. Scenarios can therefore be derived which require several simultaneous or specifically sequenced actions which would be physically impossible for a lone "insider" to accomplish. The focus of the MIT research is to extend the present technique to incorporate this time dependence so as to more effectively address the problem of sabotage of nuclear facilities by an "insider."

Investigators: Professors E. Gyftopoulos and N. Rasmussen, Dr. M. Miller; Ms. V. Dimitrijevic

The second task is in the area of international safeguards. The focus is to evaluate the credibility of material diversion scenarios in the nuclear fuel reprocessing plant using existing decision theory techniques and plant operating experience. The methodology will be applied to a specific fuel reprocessing plant.

Investigators: Dr. M. Miller and Professor M. Benedict (consultant)

Support: Sandia National Laboratories.

### 3.2.16 Development of a Safeguards Approach for a Heavy Water Production Plant

The aim of this research is to find solutions for problems identified by the IAEA, which relate to developing a practical safeguards approach for a heavy water production facility based on the monothermal ammonia/hydrogen exchange process with water feed.

Investigators: Dr. M. Miller and Professor M. Benedict (consultant)

Support: International Atomic Energy Agency (IAEA).

3.2.17 Thermal Phenomena in Severe LWR Activities

The accident at the Three Mile Island (TMI) has prompted numerous investigations of safety aspects of nuclear power plants. As a result of the sequence of events at TMI, class 9 accidents, in which the events are of low probability, gained increased attention in LWR safety analysis. In one scenario, the loss of coolant may result in partial uncovering of the core and subsequent heat-up and damage of fuel elements. When high temperature or molten core materials encounter liquid coolant, fragmentation normally occurs. The fragments may settle on horizontal surfaces such as spacer grids forming the so-called debris or rubblized bed. The fuel in these debris beds will be heated by radioactive decay of retained fission products.

This research program aims at defining the cooling potential for a degraded LWR core and determining the containment thermal response to vessel melt through, under severe accident conditions.

In the preceeding two years several have been investigated.

1. Hydrodynamics of Degraded Core Cooling

1.a. The core uncovery (boil-off) transient was studied with a two fluid model for two-phase flow. The objective was to delineate the effects of thermal and mechanical nonequilibrium and multidimensional geometry on the prediction of the two-phase mixture level. Analyses of three sets of experiments (FLECHT-SEASET, Westinghouse 336-rod bundle and semiscale TMI-2 simulation) were performed with the MIT-developed two-fluid model code THERMIT. It was found that differences in the interfacial momentum-exchange models employed greatly affected the predicted time variation of the two-phase level during the transient. The influence of the thermal nonequilibrium was not as great. The results also showed only small differences between the three-dimensional and one-dimensional calculations for the PWR geometry.

1.b. The literature on hydrodynamics of forced convection cooling of particle beds was reviewed and used to assess the characteristics of in-situ cooling of a degraded LWR reactor core under conditions representative of severe accidents. It was found that the pressure head required, for a given rate of liquid water flow, through a totally degraded core is one to two orders of magnitude higher than the case of intact core geometry. To remove decay heat of up to 1-2% of the reactor normal power, even with conservative assumptions, the pressure head is within the capability of the main reactor pumps. However, particles with very small diameter (less than 100 μm) will potentially be swept out by the flow.

2. Thermal Response to Containment and Corium-Concrete Interaction

2.a. A semi-empirical correlation based on a gas bubbling mechanism was proposed to calculate the interface heat transfer between molten corium and concrete. Heat transfer is conduction controlled, while periodic contact between corium and concrete occur at a frequency controlled by the gas generation rate. The empirical constants were obtained from reported experimental results for water or benzene overlaying dry ice. Compared with the experimental results of Sandia Laboratories for concrete attack by steel and iron-$Al_2O_3$ mixture the proposed correlation appears to lead to reasonable results.

2.b. A simplified model was used to quantify the impact of heat transfer from core melt to concrete on the pressure rise in the containment. Limited heat removal from the containment, by fan coolers, and thermal equilibrium between all components were assumed. For a PWR large dry containment, if the chemical reactions of the decomposed gases were suppressed, increased heat transfer to concrete decreases the total pressure rise in the containment. When chemical reactions of the concrete decomposition gases were assumed to occur to completion, the heat transfer to concrete had less impact on the pressure rise. This appears to hold for both basaltic and limestone concrete. For a PWR ice condensor containment the pressure response of the containment is relatively insensitive to the fraction of heat transfer to concrete. For a BWR containment, however, the pressure increases as the fraction of heat to concrete increases.

Investigators: Professors M.S. Kazimi, J. Meyer, G. Brown and C. Heising; Messrs. M. Lee, S. Mohammed, and D. Petti.

Support: Electric Power Research Institute.

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer

Recent References:

S.M. Mohammed and M.S. Kazimi, "Hydrodynamics of Degraded Core Cooling," Nucl. Eng. and Design, 71, 33-43, (1982).

C.K. Tsai, B.R. Sehgal and M.S. Kazimi, "Two Fluid Modeling of the LWR Core Uncovery Transient," Proc. 2nd Int. Mtg. on Nuclear Reactor Thermal-hydraulics, Santa Barbara, CA, (1983).

M. Lee, M.S. Kazimi and G. Brown, "A Heat Transfer Model for the Corium/ Concrete Interface," Proc. Int'l Mtg. on Severe LWR Accidents, Cambridge, MA, (1983).

M. Lee and M.S. Kazimi, "A Sensitivity Analysis of the Impact of Corium Heat Transfer to Concrete on Containment Pressure," Proc. Int'l Mtg. on Severe LWR Accidents, Cambridge, MA, (1983).

### 3.2.18 Structural Mechanics

Nuclear power plants contain components requiring application of a wide variety of structural mechanics analysis techniques. During this activities period we have performed research studies in the following application areas:

- vibration of steam generator tubes including nonlinearities of drag coefficient and of the presence of gaps at tube supports;

- defining methods for seismic qualifications of instrument cables; and

- developing a computer code to determine pressure vessel stresses and flexibilities at attachments.

Investigators: Professor J.E. Meyer; Messrs. S. Ribeiro, J.L. Griffin, B.M. Peacock, and F.M.G. Wong.

Support: Self-supporting students with NED computer funding; (through the engineering internship program) Combustion Engineering and Stone and Webster.

Related Academic Subjects:

22.314J Structural Mechanics in Nuclear Power Technology
22.42 Numerical Methods in Engineering Analysis

Recent References:

S. Ribeiro, "Mechanisms of Flow Induced Vibrations of Circular Cyclinders in Cross Flow," SM Thesis, Department of Nuclear Engineering, MIT, February 1983.

J.F. Griffin, Jr., "Few Span Vibration of Steam Generator Tubes with Support Gaps," SM Thesis, Department of Nuclear Engineering, MIT, February 1984.

B.M. Peacock, "Seismic Qualification of CEDM Power and Position Indication Cables," SB/SM Thesis, Department of Mechanical Engineering, MIT, May, 1983.
S.V. Guerreiro Ribereiro and J.E. Meyer, "Mechanisms of Flow Induced Vibrations of Circular Cylinders in Cross Flow," Trans. 7th Intl. Conf. Stru. Mech. in Reactor Tech. B, Paper B5/7, (1983).

S. Harriague and J.E. Meyer, "A Study of Friction and Axial Effects in Pellet-Clad Mechanical Interaction," in Water Reactor Fuel Element Performance Computer Modeling, J. Gittus, ed., pp. 187-217, Applied Science Publishers, England, 1983.

### 3.2.19 Advanced Instrumentation and Control Systems

It has been recognized for some time that improvements can be made in the reactor control instrumentation in the area of fault detection and identification (FDI). Some potential improvements in this area are being studied as a joint program between the Charles Stark Draper Laboratory and MIT. The goal of the program is to utilize fault detection technology that has been developed for aerospace control systems and apply it to reactor control instrumentation.

The principal features of the method involve the use of digital computers for comparison of sensors together with the use of analytic models to provide an analytic redundancy for an independent check on the sensor values. Although the general techniques exist for taking these inputs and detecting faults, the real time analytic models for the nuclear plant systems are not available. Thus the MIT studies at this time involve development of the real time analytic models and the Draper program carries overall applications of the methods for sensor validation together with fault detection and identification. An important component of this program is the demonstration of the techniques and of computer control by utilizing the MIT Research Reactor. Future considerations involve the potential for diagnostic information developed from the fault detection and eventually there is a possibility of more closed loop controls.

In addition to the Nuclear Engineering Department, the MIT group involves contributors from the Mechanical Engineering Department. In particular, control display systems are being studied for human factor engineering considerations at the man-machine interface. This work has led to a one-week Summer Session Program presented jointly by the Mechanical Engineering Department and the Nuclear Engineering Department entitled Man-Machine Interfacing in Nuclear Power and Industrial Process Control.

Draper IR&D funded task areas include reactor core modeling, plant component modeling, steam generator FDI application, MIT Reactor Feasibility Study, decision analysis technology transfer, alternate diagnostic concepts, and computer utilization concepts.

A recent Argonne breeder technology program award has given us the chance to explore new EBR-II applications. The project is intended to result in computer techniques appropriate for sensor validation during EBR-II natural circulation.

<u>Investigators</u>: Professors D.D. Lanning, J.E. Meyer, and T.B. Sheridan (Department of Mechanical Engineering); Messrs. J.A. Bernard, M.A.L. Bertodano, A. Bujanda, S.P.D. Garcia, G.M. Garner, R.V. Geiger, V. George, H.N. Jow, S.P. Kao, K.S. Kwok, R.S. Ornedo, H.P. Polenta, B.W. Rhee, W.H. Strohmayer, R. B. Vilim, R.J. Witt, and K. Wong (MIT); Drs. A. Ray, J.J. Deyst, J.H. Hopps, C.K. Whitney, and O.L. Deutsch (Draper Laboratory).

<u>Support</u>: Internal Draper Funds (IR&D), self-supporting students with NED computer funding; and Argonne Breeder Technology Program.

<u>Related Academic Subjects</u>:

22.32 Nuclear Power Reactors
22.363 Two-Phase Flow and Boiling Heat Tranfser
22.42 Numerical Methods in Engineering Analysis

Recent References:

W.H. Strohmayer, "Dynamic Modeling of Vertical U-Tube Steam Generators for Operational Safety Systems," Ph.D. Thesis, Department of Nuclear Engineering, MIT, September 1982.

K. Wong, "Computer Model of a Nuclear Reactor Primary Coolant Pump," SM Thesis, Department of Nuclear Engineering, MIT, September 1982.

M.A. Lopez de Bertodano, "Fast Computational Methods for Two Phase Flow Situations in Pressurized Water Reactors," NE/SM Thesis, Department of Nuclear Engineering, MIT, February 1983.

R.V. Geiger, "On-Line Fault-Tolerant Sensor Processing for the MIT Research Rector Using Analytic Redundancy," SM Thesis (CSDL-T-765), October 1981.

A. Bujanda, "Modeling, Simulation and Control of a Condensate System of a Nuclear Power Plant," SM Thesis, Department of Mechanical Engineering, MIT, December 1982.

R.B. Vilim, "Adaption of On-Line Analytic Models After Fault Detection," Ph.D. Thesis, Department of Nuclear Engineering, MIT, February 1983.

J.A. Bernard and A. Roy, "Experimental Evaluation of Digital Control Schemes for Nuclear Reactors," 22nd IEEE Control and Decision Conference, 1983.

### 3.2.20 Engineering for Fusion Systems Studies

As fusion technology develops, it is important that sufficient engineering is also developed to provide concepts for eventual power applications. This topic covers such studies.

Investigators: Professor J.E. Meyer; Messrs. R.J. LeClaire, J. Gullem, J.R. Zwick, and Y. Nakagawa; Ms. K.S. McCormack.

Support: DOE through the MIT Plasma Fusion Center.

Related Academic Subjects:

| | |
|---|---|
| 22.312 | Engineering of Nuclear Reactors |
| 22.33 | Nuclear Engineering Design |
| 22.363 | Two-Phase Flow and Boiling Heat Transfer |
| 22.621 | Thermonuclear Reactor Design |

Recent References:

E. Bobrov, L. Bromberg, D.R. Cohn, N. Diatchenko, R.J. LeClaire, J.E. Meyer and J.E.C. Williams, "High Field Tokamaks with DD-DT Operation and Reduced Tritium Breeding Requirements," MIT Plasma Fusion Center Report PFC/RR-83-5, February 1983.

L. Bromberg, D.R. Cohn, F. Bobrov, N. Diatchenko, R.J. LeClaire, J.E. Meyer and J.E.C. Williams, "High Field Tokamaks with DD-DT Operation and Reduced

Tritium Breeding Requirements," MIT Plasma Fusion Center Report PFC/CP-83-7, April 1983.

R.J. LeClaire, J.E. Meyer, L. Bromberg, D.R. Cohn and J.E.C. Williams, "Aspects of Long Pulse Commercial Tokamak Reactor Design," MIT Plasma Fusion Center Report, PFC/CP-83-15, (December 1983).

## 3.3 Nuclear Materials and Radiation Effects

The nuclear materials program has four major objectives: (1) to provide students in the Department with sufficient background in the principles of physical metallurgy and physical ceramics to incorporate a fuller consideration of reactor structural and fuel materials in their thesis programs; (2) to advance reactor materials technology in the areas of materials selection, component design, irradiation behavior modeling, safeguards analysis, quality assurance, and reliability assessment; (3) to conduct instructional and research programs into both the fundamental nature of radiation effects to crystalline solids and the interrelationships between radiation-induced structural problems on an interdepartmental and interdisciplinary manner in the general fields of energy conservation, energy transmission, and environmental technology as related to power production.

### 3.3.1 Subjects of Instruction

In the area of nuclear materials and radiation effects, 22.070J, Materials for Nuclear Applications, and 22.071J, Physical Metallurgy Principles for Engineers, are available for undergraduates. Graduate students can select from the other subjects described below.

22.070J: Materials for Nuclear Applications, is an introductory subject for students who are not specializing in nuclear materials. Topics covered include applications and selection of materials for use in nuclear applications, radiation damage, radiation effects and their effects on performance of materials in fission and fusion environments. The subject meets concurrently with 22.70J, but assignments differ.

22.071J: Physical Metallurgy Principles for Engineers, covers the following topics: crystallography and microstructure of engineering materials. Thermodynamics of alloys, structural theory of metallic phases. Rate processes in metals; solidification, solid state diffusion, oxidation, and phase transformation. Defect properties; point defects, dislocations and radiation damage. Mechanical properties; plastic deformation, work hardening, strengthening mechanisms and fracture. Recovery and recrystallization. Emphasis on structure-properties relationships, their physical interpretation and quantification. The subject meets concurrently with 22.71J, but assignments differ.

22.70J: Materials for Nuclear Applications, is an introductory subject for graduate students who are not specializing in nuclear materials. This subject meets concurrently with 22.070J, but assignments differ.

22.71J: Physical Metallurgy Principles for Engineers, is the introductory course in this sequence of study and is intended for graduate students who did their undergraduate work in engineering and science fields which did not provide formal instruction in metallurgy or materials science. This subject meets concurrently with 22.071J, but assignments differ. This and subsequent courses are conducted jointly between the Department of Nuclear Engineering and the Department of Materials Science and Engineering.

22.72J: Nuclear Fuels, covers topics such as the behavior of nuclear fuels and fuel element cladding materials in reactor cores. Experimental observations; phenomenological and theoretical modeling of radiation; and thermal-induced effects such as fuel and cladding swelling, fission gas release, and radiation-induced creep. Fuel design, performance modeling, and reliability analysis using state-of-the-art computer codes. Recent developments in advanced nuclear and fusion related core materials are discussed.

22.73J: Radiation Effects in Crystalline Solids, is designed for graduate students of nuclear engineering, materials science and physics desiring a detailed background in the physics of radiation damage and the characteristics of crystal defects and defect interactions. Unified treatment based on governing principles in defect structures, thermodynamics and kinetics of equilibrium and nonequilibriuum systems. Discusses phenomena of radiation effects in metals and nonmetals used in fission reactors, fusion reactors, nuclear waste encapsulation, and ion beam technology. Topics include defect generation, damage evolution, radiation enhanced and induced rate processes, radiation effects on mechanical and physical properties.

22.75J: Radiation Effects in Reactor Structural Materials, acquaints both nuclear engineering and metallurgy students with the classes and characteristics of structural materials used in the core and primary circuits of fission and fusion reactor systems. The effects of neutron irradiation and coolant environments on strength, brittle fracture, high-temperature embrittlement, creep and growth, void swelling, and corrosive behavior are discussed in terms of mechanisms and practical consequences to component design and system operation. Emphasis is also given to materials specifications and standards for nuclear service, quality assurance, and reliability assessment.

22.76J: Introduction to Nuclear Chemical Engineering, deals with applications of chemical engineering to the processing of materials for and from both nuclear fission and fusion reaction. Covers topics such as principles and techniques for separation of uranium, hydrogen, and other isotopes; tritium handling; solvent extraction and ion exchange as applied to nuclear materials, including processing of irradiated fuel from fission reactors and extraction and purification of uranium from its ores; chemistry of uranium, plutonium, and fission products.

### 3.3.2 Hydrogen Embrittlement and Corrosion Fatigue of Nickel-Base Alloys for Nuclear Steam Generator Applications

An investigation is being conducted to investigate the effect of hydrogen and other environmental factors on the cracking susceptibility of Inconel-600, X-750 at room temperature and at nuclear steam generator operating conditions. This investigation will aid in the understanding of several phenomena, including denting, and stress corrosion cracking, which have led to a loss in availability of many nuclear electric generating stations.

Investigators: Professors R.M. Latanision and R.M.N. Pelloux (Department of Materials Science and Engineering); Messrs. R. Ballinger, W.C. Moshier and Ms. K. Siedein.

Support: Electric Power Research Institute

Related Academic Subjects:

22.71J Physical Metallurgy Principles for Engineers
3.54 Corrosion - The Environmental Degradation of Materials

Recent References:

R.M. Latanision, R.M.N. Pelloux, R. Ballinger, W. Moshier, "The Role of Uncertainty in Measurement of Crack Lengths in the Role of Compliance," Presented at the IAEA Specialists Meeting on Subcritical Crack Growth, Frieburg, W. Germany, (May 13-15, 1981).

### 3.3.3 Precipitation Mechanisms and Sequences in Rapidly Cooled Ni-Nb Alloys

Rapid cooling from the melt (splat cooling) is capable of producing highly non-equilibrium microstructures--especially regarding solute supersaturation and crystal structure. Irradiation may push the system further into irreversibility, and in conjunction with rapid cooling may give phases and precipitation sequences never before observed. We have irradiated amorphous and microcrystalline samples of 60-40 Ni-Nb and microcrystalline samples of 85-15 Ni-Nb with 3 MeV $Ni^{+}$ ions in the Oak Ridge National Laboratory accelerator. The temperatures (700-1000 K), atomic displacement rate ($10^{-3}$ displacements/atom sec), and dose (2 and 20 displacements/atom) were chosen to optimize irradiation altered phase stability. The irradiated samples and samples reacted thermally have been studied by electron microscopy--TEM and STEM--in the CMSE facility. These microcrystalline and partly amorphous alloys were found to be very resistant to radiation damage, which makes them attractive candidates for advanced fusion power systems.

Investigators: Professor K.C. Russell and Dr. R.S. Chernock

Support: National Science Foundation.

Related Academic Subjects:

22.73J Radiation Effects in Crystalline Solids
22.75J Radiation Effects to Reactor Structural Materials

Recent References:

K.C. Russell, "Precipitate Nucleation during Irradiation," in Phase Stability during Irradiation, eds. J.R. Holland, L.K. Mansur and D.I. Potter, TMS-AIME, Warrendale, PA (1981) pp. 507-520.

R.S. Chernock and K.C. Russell, "Phase Stability in Rapidly Cooled Ni-Nb Alloys under $Ni^{++}$ Ion Irradiation," Acta Metall. (in press).

K.C. Russell, "Phase Stability Under Irradiation," to appear in Progress in Materials Science, ed. J. Christian, P. Haasen and T.B. Massalski, Pergamon Press, Oxford.

### 3.3.4 Defect Aggregation in Irradiated Materials

This is a combined theoretical and experimental study of defect aggregation in irradiated metals and ceramics. We have modeled irradiation-induced swelling in dual-ion-irradiated stainless steel in cooperation with an experimental study, and found good agreement with their results. We have $Ni^+$-ion irradiated Fe-Ni-C alloys in an effort to induce carbide precipitation where such would not occur thermally. Preliminary electron microscope studies indicate such precipitation, which has important implications in fission and fusion reactor materials. We are in the early stages of a combined theoretical and experimental study of radiation resolution of TiC and $TiO_2$ precipitate particles in a Ni matrix. This study should show the feasibility of using such materials in a fission or fusion environment. We are studying the effects of fast neutron and high energy electron irradiation on the microstructures of two ceramics, AlON and $MgAl_2O_4$, to determine their response to fission and fusion environments. The two materials are highly damage-resistant.

Investigators: Professors K.C. Russell and L.W. Hobbs, Dr. H.J. Frost; Ms. S.E. Best, Messrs. Se-Yong Oh and C.A. Parker.

Support: National Science Foundation.

Related Academic Subjects:

22.73J Radiation Effects in Crystalline Solids
22.75J Radiation Effects to Reactor Structural Materials

Recent References:

H.J. Frost and K.C. Russell, "Precipitate Stability under Irradiation," in Phase Transformations during Irradiation, ed. F.V. Nolfi, Jr., Applied Sci. Publ., NY, London, (1983) pp. 75-113.

H.J. Frost and K.C. Russell, "Recoil Resolution and Particle Stability under Irradiation," J. Nucl. Mater., 103 & 104, 1427-1432, (1981).

C.A. Parker and K.C. Russell, "Cavity Nucleation Calculations for Irradiated Metals," J. Nucl. Mater. (in press).

C.A. Parker and K.C. Russell, "Void Nucleation in Metals Assisted by Non-Ideal Inert Gas," Scripta Metall., 15, 643-647, (1981).

### 3.3.5 Phase Stability and Irradiation Effects

Phase stability in nuclear materials is dictated by local composition, local and external field, and microscopic fluctuations. We have studied such effects theoretically and experimentally. The theoretical studies to date have included solute segregation, void nucleation, and irradiation creep/-growth. The experimental study has focused on the magnetic effect on ferritic stainless steels.

Investigators: Professor I-W. Chen; Messrs. E. Faillace, A. Taiwo and P. Kalish.

Support: National Science Foundation.

Related Academic Subject:

22.73J Radiation Effects in Crystalline Solids

Recent Publications:

I-W. Chen, "Irradiation Induced Solute Segregation in Multi-component Alloys," J. Nucl. Mater., 116, 249, (1983).

I-W. Chen, E. Faillace and A.P. Miodownik, "The Effect of a Magnetic Field on Phase Transformations in Fe-Cv Alloys," in Ferritic Steels in Nuclear Technologies, Eds. J.W. David and D.J. Michel, AIME, in press, (1983).

I-W. Chen, "Magnetic Field Induced Growth of Ferromagnetic Materials under Irradiation," in Ferritic Steels in Nuclear Technologies, Eds. J.W. Davis and D.J. Michel, AIME, in press, (1983).

I-W. Chen, "Anisotropic Diffusion of Point Defects to an Edge Dislocation," J. Nucl. Mater., in press, (1984).

I-W. Chen, "Void Nucleation under Non-Equilibrium Solute Segregation. A Stability Analysis," J. Nucl. Mater., in press, (1984).

I-W. Chen, "The Potential of Lead Alloys as the Candidate Materials for Radioactive Waste Disposal," Final Report, MLM-324, ILZRO, (1982).

### 3.3.6 Deformation and Fracture at Elevated Temperatures

Deformation and fracture at elevated temperatures involve diffusional and grain-boundary processes, in addition to the common mechanisms operational at lower temperatures. Our studies in this area have included the nucleation and growth mechanisms of creep cavitation, diffusional creep, dislocation creep and fine-grain superplasticity.

Investigators: Professor I-W. Chen, Dr. M.H. Yoo (ORNL); Mr. M. Capano

Support: Department of Energy.

Related Academic Subject:

22.71J (22.071J) Physical Metallurgy Principles for Engineers

Recent Publications:

I-W. Chen, "Migration Assisted Diffusional Creep by Grain-Boundary Diffusion," Acta Metall., 30, 1317, (1982).
I-W. Chen, "Diffusional Creep in Two-Phase Materials," Acta Metall., 30, 1655, (1982).

I-W, Chen, "Mechanisms of Cavity Growth in Creep," Scripta Metall., 17, 17, (1983).

I-W. Chen, "Cavity Growth on a Sliding Grain-Boundary," Metall. Tran., 14A, 2289, (1983).

I-W. Chen, "Effects of Boundary Mobility and Phase Equilibrium on Kinetic Processes of Multi-component Polyphase Ceramics," in Advances in Ceramics, Vol. 9, Eds. M.F. Yan and A.H. Heuer, American Ceramic Society, in press (1982).

I-W. Chen and M.F. Yoo, "Creep Cavitation under Interfacial Segregation," Acta Metall., in press, (1984).

### 3.3.7 Martensitic Transformations

Martensitic transformations exist in numerous materials, such as iron, plutonium and zirconia. They have the characteristics of a displacive transformation with a large lattice distortion. These transformations have been studied with the intent of understanding a potential toughening mechanism. Our studies of martensitic transformations have focused on the mechanism for nucleation, and its interrelation with the size statistics, the shape effect and the stress effect.

Investigators: Professor I-W. Chen and Mr. Y-H. Chiao

Support: Department of Energy.

Related Academic Subject:

22.71J (22.071J) Physical Metallurgy Principles for Engineers

Recent Publications:

I-W. Chen and Y.H. Chiao, "Martensitic Nucleation in $ZrO_2$," Acta Metall., 31, 1627, (1983).

I-W. Chen and Y.H. Chiao, "Martensitic Nucleation in $ZrO_2$ and $HfO_2$--An Assessment of Small Particle Experiments with Metal and Ceramic Matrices," in Advances in Ceramics, Eds. N. Claussen, M. Rhule and A.H. Heuer, American Ceramics Society, in press, (1983).

### 3.3.8 Experimental and Theoretical Studies of Radiation Damage in Future Fusion Reactors

The fast neutron radiation fields in future controlled thermonuclear reactors (CTR's) will adversely affect the mechanical properties of first wall structural material. Development of the required understanding of damage effects and a design data base are needed prior to the design of the experimental power and demonstration power reactors (EPR and DPR). Facilities used to test materials for fusion reactor applications are inadequate since the gas production associated with displacement damage in the CTR cannot readily be simulated in a fast fission reactor, a need has developed for CTR damage simulation. Our research effort in this project has been directed (1) toward the development of simulation techniques for synergistic helium and damage production and (2) toward improving the understanding of the effects of near surface damage and gas implantation upon the mechanical properties of the first wall of fusion reactors. In the first task area, techniques are under development for homogeneous alloy doping with $^{10}B$, to permit simultaneous generation of helium and displacement damage during reactor irradiations. In the second task area an in-core fatigue cracking experiment was successfully carried out. This experiment simulated much of the environment expected at the fusion reactor first wall. Surface bombardment, bulk irradiation damage and strain cycling were all incorporated into this experiment.

Investigators: Professor O.K. Harling; Drs. N. Kanani, M. Lee; Messrs. H. Andresen, G. Kohse, S. DiPietro, O. Boydas.

Support: U.S. Department of Energy.

Related Academic Subjects:

22.612 Introduction to Plasma Physics II
22.73J Radiation Effects in Crystalline Solids
22.75J Radiation Effects in Reactor Structural Materials

Recent References:

H. Andresen, G. Kohse, A.S. Argon and O.K. Harling, "A Scoping Experiment to Investigate the Effects of Simultaneous Multi-Energy Ion Bombardment, Neutron Irradiation and Stress/Temperature Cycling on 316 SS," J. Nucl. Mater., 103 & 104, (1981) 1011-1016.

H. Andresen, S. DiPietro, G. Kohse and O.K. Harling, "The Behavior of Boron Coatings Under Simultaneous Ion Bombardment and Temperature Cycling," J. Nucl. Mater., 103 & 104, (1981) 363-368.

G. Kohse and O.K. Harling, "A Fatigue Test for Specimens from Simultaneously Ion-Bombarded and Stress/Temperature Cycled SS316 Pressurized Tubes," DAFS Quarterly Report, USDOE, (October-December 1981).

M.P. Manahan, A.S. Argon and O.K. Harling, "Mechanical Behavior Evaluation Using the Miniaturized Disk Bend Test," DAFS Quarterly Report, USDOE (October-December 1981).

G. Kohse and O.K. Harling, "The Effects of Multi-Energy Ion Bombardment, Neutron Irradiation and Stress/Temperature Cycling on Fatigue Failure of 316SS," J. Nucl. Mater., 111 & 112, (1982) 699-703.

J. Megusar, O.K. Harling and N.J. Grant, "Lithium Doping of 316 Stainless Steel to Simulate Irradiation Damage in a Fusion Reactor Environment," DAFS Quarterly Report, USDOE, (April-June 1982).

G. Kohse and O.K. Harling, "Ion Bombardment Effects on the Fatigue Life of Stainless Steel Under Simulated Fusion First Wall Conditions," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Las Vegas, Nevada (September 19-22, 1983), to be published in the J. Nucl. Mater.

G. Kohse and O.K. Harling, "Suppression of Blistering in a Broadly Distributed Ion Implantation Under Simulated Fusion First Wall Conditions," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Las Vegas, Nevada (September 19-22, 1983), to be published in the J. Nucl. Mater.

### 3.3.9 Radioactive Corrosion Products in the Primary Coolant Systems of Light Water Power Reactors

High radiation exposures to workers during maintenance of the primary coolant systems of present light water power reactors results in a significant cost which must be borne by the power consumers. The MITR is well suited to the development of an experimental facility which would be devoted to studying the basic processes involved in the production, activation and transport of radioactive corrosion products. A technical team comprising MIT staff members, from various relevant disciplines, is actively developing a proposal for an in-core loop at MITR which is designed to simulate part of the primary coolant system of a PWR.

Investigators: Professors O.K. Harling, D.D. Lanning, R. Latanision (Department of Materials Science and Engineering), M. Driscoll, and R. Ballinger; Mr. J. Bernard.

Support: U.S. Energy Research and Development Administration via Energy Laboratory and MIT internal funds.

Related Academic Subjects:

22.71J Physical Metallurgy Principles for Engineers
22.75J Radiation Effects in Reactor Structural Materials

### 3.3.10 The Development of Advanced Primary First Wall Alloys

The severe environment of future fusion reactors is expected to drastically limit the lifetime of the first wall structures if currently available materials are used in reactor construction. In this major research effort a broad ranging interdisciplinary approach is being applied to the development of improved structural alloys for the first walls of fusion reactors. The approach used in this project includes:

1. a determination of the structural alloy requirements based on an analysis of fusion reactor design,

2. production of carefully chosen test lots of alloy by rapid solidification from the melt,

3. microstructural characterization of pre and post irradiation,

4. mechanical property testing of unirradiated material,

5. modeling of mechanical behavior, and microstructural irradiation response,

6. design of new improved alloys, production and testing and analysis of results.

Investigators: Professors O.K. Harling, N.J. Grant (Department of Materials Science and Engineering), and J.B. Vander Sande (Department of Materials Science and Engineering); Drs. J. Megusar, N. Kanani, M. Lee and D. Imeson; Messrs. A. Adegbulugbe, K. Genssler, M. Manahan, E. Testart, G.P. Yu, D.S. Sohn, A. Chaudry and A. Ibrahim.

Support: U.S. Department of Energy

Related Academic Subjects:

22.612 Introduction to Plasma Physics II
22.73J Radiation Effects in Crystalline Solids
22.75J Radiation Effects in Reactor Structural Materials

Recent References:

G.P. Yu, "Relationship of Material Properties to the Design of a Fusion Reactor First Wall," Sc.D. Thesis, Department of Nuclear Engineering, MIT, May 1981.

A.O. Adegbulugbe, "Structural Design Limits for Fusion First Walls," Sc.D. Thesis, Department of Nuclear Engineering, MIT, May 1981.

J. Megusar, O.K. Harling and N.J. Grant, "Potential for Using Rapid Solidification for Improved Irradiation Performance in the Fusion Environment," J. Nucl. Mater., 103 & 104, (1981) 961-966.

J. Megusar, L. Arnberg, J.B. Vander Sande and N.J. Grant, "Microstructure of Rapidly Solidified $Al_2O_3$ Dispersion Strengthened Type 316 Stainless Steel," J. Nucl. Mater., 103 & 104, (1981) 1109-1114.

N. Kanani, L. Arnberg and O.K. Harling,"Pre-Irradiation Spatial Distribution and Stability of Boride Particles in Rapidly Solidified Boron Doped Stainless Steels," J. Nucl. Mater., 103 & 104, (1981) 1115-1120.

E. Testart, J. Megusar, L. Arnberg and N.J. Grant, "Mechanical Properties and Structure of Rapidly Solidified High Titanium Stabilized 316 Stainless Steel," J. Nucl. Mater., 103 & 104, (1981) 833-838.

L. Arnberg, J. Megusar, D. Imeson, H.J. Frost, J.B. Vander Sande, O.K. Harling and N.J. Grant, "The Microstructure of Neutron Irradiated Rapidly Solidified Path A Prime Candidate Alloys," J. Nucl. Mater., 103 & 104, (1981) 1005-1010.

L. Arnberg, J. B. Vander Sande, H.J. Frost and O.K. Harling, "The Microstructure of Rapidly Solidified Path A Prime Candidate Alloys Following Irradiation with Fe and He Ions," J. Nucl. Mater., 103 & 104, (1981) 1069-1074.

J. Megusar, L. Arnberg, J.B. Vander Sande and N.J. Grant, "Microstructures of Rapidly Solidified Path A Prime Candidate Alloys," J. Nucl. Mater., 103 & 104, (1981) 1103-1108.

O.K. Harling, G.P. Yu, N.J. Grant and J.E. Meyer, "Application of High Strengh Copper Alloys for a Fusion Reactor First Wall," J. Nucl. Mater., 103 & 104, (1981) 127-132.

A.O. Adegbulugbe and J.E. Meyer, "Failure Criteria for Fusion Reactor First Wall Structural Design," J. Nucl. Mater., 103 & 104, (1981) 161-166.

M.P. Manahan, A.S. Argon and O.K. Harling, "The Development of a Miniaturized Disk Bend Test for the Determination of Postirradiation Mechanical Properties," J. Nucl. Mater., 103 & 104, (1981) 1545-1550.

J. Megusar and N.J. Grant, "Stabilization and Strengthening of $Pd_{80}Si_{20}$ Metallic Glass," Mat. Sci. Eng., 49, (1981) 275-283.

J. Megusar, L. Arnberg, J.B. Vander Sande and N .J. Grant, "Optimization of Structure and Properties of Path A Prime Candidate Alloy (PCA) by Rapid Solidification," J. Nucl. Mater., 99, Nos. 2 & 3, (1981) 109-202.

H.J. Frost and K.C. Russell, "Particle Stability with Recoil Resolution," Acta Met., 30, (1982) 953-960.

H.J. Frost and K.C. Russell, "Precipitate Stability Under Irradiation (to appear in Phase Transformations and Solute Redistribution in Alloys During Irradiation," a Res Mechanica Monograph).

M.P. Manahan, "A New Postirradiation Mechanical Behavior Test-The Miniaturized Disk Bend Test, ANS Trans. 23, (1982) 352-354.

J. Megusar, O.K. Harling and N.J. Grant, "Lithium Doping of Candidate Fusion Reactor Alloys to Simulate Simultaneous Helium and Damage Production," accepted for publication in J. of Nucl. Mater.

J. Megusar, D. Imeson, J.B. Vander Sande and N.J. Grant, "Dynamic Powder Compaction of Rapidly Solidified Path A Alloy with Increased Carbon and Titanium Content," Fifteenth ADIP Semiannual Progress Report, October 1981-March 1982.

A.I. Ibrahim, J. Megusar and N.J. Grant, "Mechanical Properties and Structure of $Y_2O_3$ Dispersion Stabilized, Rapidly Soldified 316 Type Stainless Steel," Fifteenth ADIP Semiannual Progress Report, October 1981-March 1982.

D. Imeson, C. Tong, J.B. Vander Sande and O.K. Harling, "The Effect of Neutron Irradiation on the Titanium Carbide Distribution in Rapidly Solidified Austenitic Stainless Steels of Varying Titanium and Carbon Content," a paper submitted at the symposium on the Chemistry and Physics of Rapidly Solidified Materials, 1982 TMS-AIME Fall Meeting, St. Louis, Missouri, October 24-28, 1982.

D. Imeson, M. Lee, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part I: Microstructural Response to Neutron Irradiation," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-23, 1983, to be published in the J. Nucl. Mater.

C.H. Tong, D. Imeson, J. Megusar, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part II: Dual Ion Irradiations," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-23, 1983, to be published in the J. Nucl. Mater.

D. Imeson, C.H. Tong, C.A. Parker, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part III: A Model for the Effect of Titanium Addition," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-23, 1983, to be published in the J. Nucl. Mater.

M. Lee, D.S. Sohn, N.J. Grant and O.K. Harling, "Miniaturized Disk Bend Tests of Neutron Irradiated Path A Type Alloys," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-22, 1983, to be published in the J. Nucl. Mater.

J. Megusar, E. Lavernia, P. Domalavage, O.K. Harling and N.J. Grant, "Structures and Properties of Rapidly Solidified 9Cr-1Mo Steel," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-22, 1983, to be published in the J. Nucl. Mater.

O.K. Harling, M. Lee, D.S. Sohn, G. Kohse and C.W. Lau, "The MIT Miniaturized Disk Bend Test," an invited paper presented at the Symposium on Use of Non-Standard Sub-Sized Specimens for Irradiated Testing, Albuquerque, New Mexico, September 23, 1983, to be published in Symposium Proceedings in an ASTM Special Technical Publication.

## 3.4 Nuclear Chemical Technology

Many parts of the nuclear fuel cycle outside of the reactor involve large scale chemical reactions. These include the preparation of uranium ore, the enrichment of uranium, the reprocessing of special fuel and waste disposal operations. In dealing with these important problems, a knowledge of nuclear chemical engineering is vital.

### 3.4.1 Subject of Instruction

22.76J Introduction to Nuclear Chemical Engineering, deals with applications of chemical engineering to the processing of materials for and from both nuclear fission and fusion reactors. Topics covered include the principles and techniques for separation of uranium, hydrogen, and other isotopes; tritium handling; solvent extraction and ion exchange as applied to nuclear materials, including processing of irradiated fuel from fission reactors and extraction and purification of uranium from its ores; chemistry of uranium, plutonium, and fission products.

This subject is open to qualified undergraduate students.

### 3.4.2 Extraction of Uranium from Seawater

Work continues on the evaluation of sorbers and contactor system concepts for the recovery of uranium from seawater.

Work was completed on a two-year research program to evaluate acrylic amidoxime-type chelating ion exchange resins, prepared by the Rohm and Haas Corporation, for their uranium uptake. Specimens of some two dozen resin variations were exposed to natural seawater in test rigs at the Woods Hole Oceanographic Institution, and analyzed for uranium using delayed neutron counting at the MIT Research Reactor. Results comparable to those obtained by other workers in Japan and Germany were obtained, confirming the leading role of this material for the subject application.

Detailed analytic studies of mass transfer processes for various sorber configurations, and an evaluation of a high performance seawater contactor concept have been completed.

Work on fiber-type sorbers and on passive current-driven contactor concepts is currently underway.

Investigators: Professor M.J. Driscoll; Dr. F.R. Best, Ms. C.K. Nitta, Messrs. J. Varela, N.A. Ismail, J. Borzekowski, and P.B. Romanik.

Support: U.S. Department of Energy (terminated).

Related Academic Subjects:

22.76J Introduction to Nuclear Chemical Engineering

Recent References:

F.R. Best, M.J. Driscoll and C. Nitta, "Recovery of Uranium from Seawater," Proceedings, AICHE Conference, 74th Annual Meeting, New Orleans, Louisiana, November 8-12, 1981.

M.J. Driscoll and F.R. Best, "Systems Studies on the Extraction of Uranium from Seawater," MIT-EL-81-038, November 1981.

C.K. Nitta, F.R. Best and M.J. Driscoll, "Delayed Neutron Assay to Test Sorbers for Uranium-from-Seawater Applications," MIT-EL-82-008, February 1982; also submitted as SM Thesis.

P.B. Romanik, "Process Design Using ASPEN of a Uranium-from-Seawater Recovery System,"SB Thesis, Chemical Engineering Department, MIT, May 1982.

J. Borzekowski, M.J. Driscoll, F.R. Best, "Uranium from Seawater Research: Final Progress Report, FY '82," MIT-EL-82-037, September 1982.

M.J. Driscoll and F.R. Best (Eds.), "Progress Toward the Recovery of Uranium from Seawater," MITNE-256, December 1982.

J. Borzekowski, "Evaluation of Ion Exchange Media for the Recovery of Uranium from Seawater," SM Thesis, Department of Nuclear Engineering, MIT, February 1982.

J. Varela, "Mass and Momentum Transfer in Uranium-from-Seawater Sorption," SM Thesis, Department of Nuclear Engineering, MIT, May 1983.

N.A. Ismail, "Engineering System Analysis of Uranium Recovery from Seawater," Nucl. Eng. Thesis, Department of Nuclear Engineering, MIT, May 1983.

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M.J. Driscoll, "Recent Work at MIT on Uranium Recovery from Seawater," International Meeting on Recovery of Uranium from Seawater, Atomic Energy Society of Japan/IAEA, Tokyo, Japan, October 1983.

## 3.5 MIT Reactor

The MIT Reactor has operated since 1958, most recently at a thermal power of 5,000 kw. Neutrons and gamma rays produced by the reactor have been used by many investigators for a great variety of research projects in physics, chemistry, geology, engineering and medicine. On May 24, 1974, the reactor was shut down to make preplanned modifications that were designed to modernize the reactor and to enhance the neutron flux available to experimenters. The modification was completed by the summer of 1975, and start-up procedures were carried out during the fall of 1975. Operations up to power levels of 2,500 kw were continued until November 1976. Since November 1976 the reactor has been in routine operation at the 5,000 kw power level.

The modified reactor core is more compact than the former core and is cooled by light water instead of by heavy water. The new core is surrounded by a heavy water reflector. The core is undermoderated and delivers a high output of fast neutrons to the heavy water reflector, where the neutrons are moderated and the resulting thermal neutrons trapped to produce the desired high flux. The beam ports of MITR-II are extended into the heavy water reflector beneath the core to give experimenters a high flux of thermal neutrons with low background of fast neutrons and gamma rays. To provide the desired 5 MW of thermal power (in a more compact core) a new design of fuel plate with longitudinal ribs has been developed. Fuel elements contain 15 plates and are rhomboidal in cross section for assembly into a hexagonal close-packed core.

The modification makes use of all of the existing reactor components except the reactor tank, fuel elements, control rods and drives and top shield plugs. Parts of the former reactor that remain include the graphite reflector, thermal shield, biological shield, beam ports, heat exchangers, pumps, cooling towers and containment building.

Engineering studies and experiments on aspects of the new core have provided many opportunities for student research and participation and give unique practical training. Topics investigated by students include reactor physics calculations, neutron transport measurements in a mock-up of the new beam port and reflector configuration, fluid flow measurements on a hydraulic mock-up, heat transfer measurement and theoretical calculations on finned plates, safety analysis and fuel management studies, and construction, start up and checkout operation of the modified reactor. Recent studies are in the area of experimental-facility design, fuel management, advanced control systems and in the use of waste heat from the reactor for heating a significant part of the MIT building complex.

While the MITR-II is no longer in the NED, there is a close relationship between the Nuclear Reactor Laboratory and NED. The director of the Nuclear Reactor Laboratory is Otto K. Harling, Professor of Nuclear Engineering, and he is strongly interested in developing NED projects and uses of the MITR-II. The rise of the reactor for nuclear materials research and for teaching of NED subjects is an example.

Investigators: Professors A.S. Argon, G.L. Brownell, I.W. Chen, S.H. Chen, M.J. Driscoll, F.A. Frey, O.K. Harling, D.D. Lanning, P.M. Newberne, A.F. Sarofim, G.M. Simmons, C.G. Shull, R.M. Snapka, N.E. Todreas, V.R. Young, A. Zeilinger; Drs. C.V. Berney, L.J. Caruso, C.H. Handwerker, P. Ila, N. Istfan, M. Janghorbani, G. Kohse, M. Lee, A. Nahapetian, B. Ting, B.W. Wessels; Messrs. H. Andresen, J. Arthur, D. Atwood, T. Beatty, J. Bernard, C.Y. Chen, M. Christensen, L. Clark, S. DePietro, W. Fecych, K. Finkelstein, L. Gulen, M. Horne, M. Izenson, J. Kirsch, K. Kwok, M. Manahan, T. Nguyen, W. Pergram, G. Ray, M. Roden, T. Sando, P. Sirichakwal, H. Stockman, T. Takala; Mses. M. Ashtari, R. Hickey, S. Reilly, M. Sirichakwal, P. Sirichakwal, A. Sundaresan.

Support: MIT Reactor Depreciation Account and Reactor Operating Research Account.

Related Academic Subjects:

22.32 Nuclear Power Reactors
22.33 Nuclear Engineering Design
22.313 Advanced Engineering of Nuclear Reactors
22.314J Structural Mechanics in Nuclear Power Technology

Recent References: (reactor engineering and reactor physics only):

G.D. Dooley, "The Application of Three Dimensional Reactor Physics Calculations Utilizing Synthesis Techniques," SM Thesis, Department of Nuclear Engineering, MIT, (1979).

A.O. Adegbulugbe, "Radioactive Waste Handling and Shipment for MITR-II," SM Thesis, Department of Nuclear Engineering, MIT, (1979).

J.A. Bernard, Jr., "MITR-II Fuel Management, Core Depletion, and Analysis: Codes Developed for the Diffusion Theory Program Citation," SM Thesis, Department of Nuclear Engineering, MIT, (1979).

NOTE: References shown here emphasize reactor physics and engineering and do not include a large number of papers, reports and theses in research areas such as beam tube research in physics and chemistry, trace analysis and radiochemistry studies in nutrition, geochemistry, nuclear medicine, materials research, etc. Much more comprehensive information about research activities at the MITR-II is contained in references such as MITNRL-001, Report of Educational and Research Activities for Academic Years 1975-76, 1976-77, 1977-78.

## 3.6 Applied Radiation Physics

This program is concerned with studies of scientific and technological utilization of nuclear and atomic radiations. It is composed of a number of separate and yet related areas of teaching and research. Condensed matter science, described in this section, involves neutron and laser scattering spectroscopy and atomistic simulation of materials properties and behavior.

Other areas: Biological and medical applications (Sect. 3.7), radiological sciences (Sect. 3.8) and health radiation physics (Sect. 3.9) will be described separately. Five faculty members are currently involved in teaching and research in these areas. Recently they have joined with three faculty members in the Nuclear Materials Program to form the Radiation Science and Technology Group. It is anticipated that the existence of this Group will stimulate cooperation in various forms leading to a stronger and more unified program.

### 3.6.1 Subjects of Instruction

In the area of applied radiation physics, the following subjects of instruction are offered:

22.02: Introduction to Applied Nuclear Physics, is an introductory subject to nuclear physics and neutron physics with emphasis on those aspects of the subject which are applied in nuclear engineering. Topics covered include elementary results of quantum theory and special relativity, detection of atomic and nuclear particles, properties of atomic nuclei; isotopes and isotopic masses; nuclear reactions; natural and artificially induced radioactivity; cross sections for nuclear reactions; alpha-, beta- and gamma-decay; nuclear models; shell-models; liquid-drop model; nuclear fission properties of fission and their relation to the feasibility of nuclear power and to its problems; slowing down and diffusion of neutrons; neutron induced chain reactions.

22.04: Radiation Effects and Uses, deals with current problems in science, technology, health and environment which involve radiation effects and their utilization. Material properties under nuclear radiations. Medical and industrial applications of radioisotopes. Radiation and lasers in research. Radioactive pollutants and demographic effects. Laboratory demonstrations of methods and instruments in radiation measurements at the MIT Reactor.

22.09: Introductory Nuclear Measurements Laboratory, deals with the basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis, introduction to electronics in nuclear instrumentation; counting experiments using Geiger-Muller counter, gas-filled proportional counter, scintillation counter, and semiconductor detectors. A term project emphasizes applications to experimental neutron physics, radiation physics, health physics and reactor technology.

22.111: Nuclear Physics for Engineers I, deals with basic nuclear physics for advanced students majoring in engineering. Basic properties of nucleus and nuclear radiation. Quantum mechanical calculation of bound states and transmission coefficients. Nuclear force and nuclear shell model. Nuclear binding energy and stability. Interaction of charged particles, neutrons, gammas with matter. Nuclear decays. Introductory nuclear reactions.

22.112: Nuclear Physics for Engineers II, is a continuation of 22.111 with emphasis on detailed studies of nuclear reactions, gamma and charged particle interactions. Cross section calculations using optical models. Neutron thermalization, inelastic scattering and radiative capture. Charged particle emissions, photonuclear reactions. Fusion reactions. Availability and accuracy of current nuclear data files.

22.29: Nuclear Measurements Laboratory, deals with the principles of interaction of nuclear radiations with matter. Principles underlying instrumental methods for detection and energy determination of gamma rays, neutrons and charged particles. Applications to applied radiation physics, health physics, and reactor technology. Laboratory experiments on gas-filled, scintillation, and semiconductor detectors; nuclear electronics such as pulse amplifiers, multi-channel analysers, and coincidence techniques; applications to neutron activation analysis, X-ray fluorescence analysis, thermal neutron cross sections and radiation dosimetry.

22.44J: Computation Methods in Materials Science and Engineering, covers the principles and applications of methods for computing materials properties and behavior; atomistic simulation techniques of molecular statics, molecular dynamics and Monte Carlo as applied to crystalline solids with and without defects. Continuum modeling of fluid flow phenomena in materials processing. Finite element methods. Statistical techniques of error propagation and multivariate error analysis in experimental design. Hands-on experience using existing computer programs and programs developed during the term.

22.51: Radiation Interactions and Applications, deals with the basic principles of interaction of electromagnetic radiation, thermal neutrons, and charged particles with matter. Introduction to classical electrodynamics, quantum theory of radiation field and time-dependent perturbation theory. Emphasis is on the development of transition probabilities and cross sections describing interaction of various radiations with atomic systems. Applications include emission and absorption of light, theory of gas lasers, Rayleigh, Brillouin, and Raman scattering, X-ray diffraction, photoelectric effect, Compton scattering, Bremsstrahlung, and interaction of intense light with plasma. The last part deals with use of thermal neutron scattering as a tool in condensed matter research.

22.55J: Biological and Medical Applications of Radiation and Radioisotopes, covers the principles of radiation production and interactions. Radiation dosimetry with emphasis on applications and health hazards. Shielding of beta, gamma and neutron radiation from isotope and machine sources. Detection and spectroscopy of beta, gamma, and neutron radiation. Neutron activation analysis. Production of radioisotopes and radiopharmaceuticals. Principles of nuclear medicine. Requires a comprehensive term paper and presentation.

22.57J: Radiation Biophysics, covers radiobiology, in vivo models for radiation effects on tumors, mathematical models of cell survival, radiation chemistry, diagnostic radiology and radiation therapy. The contents of this course evolve as new information becomes available for analysis.

Subject 22.111 is taken by practically all the graduate students in the Department. Most of the undergraduates take 22.09 and many will take 22.02. All the doctoral students in Applied Radiation Physics will take 22.112, 22.29, 22.51, and 22.57J.

### 3.6.2 Neutron Spectrometry and Molecular Dynamics in Solids and Fluids

Density fluctuations occur in all forms of matter because of thermal motions of the atoms and molecules. Since these fluctuations result in space- and time-dependent inhomogeneities in the system, they can be observed directly by thermal-neutron scattering. In this way one has a powerful technique for studying molecular dynamics on a microscopic level (frequencies and wavelengths of the order of $10^{15}$Hz and one Angstrom).

A three-axis crystal spectrometer has been constructed at the MIT Reactor and put into operation in 1971. The principal study conducted during the period 1971-1976 was a series of measurements of incoherent scattering in hydrogen gases pressurized up to 200 atmospheres. The density dependence of the self-diffusion coefficient was studied through the observed quasi-elastic line width, and the data confirmed the recent prediction (based on computer molecular dynamics simulation results) of correlation effects in dense fluids. The wave number dependence of the observed line width clearly showed deviations from behavior characteristics of hydrodynamic fluctuations. Such effects have been analyzed using kinetic theory as well as results obtained from computer simulation experiments (see Section 3.6.4).

The primary purpose of this program is to apply the technique of incoherent inelastic neutron scattering to problems of molecular vibrations in large organic molecules and hydrogen-bonded solids. In the scattering event, the neutron interacts mainly with the nuclei of the atoms composing the sample rather than with the surrounding electrons. Since neutron scattering cross sections are well known for most elements, the scattering can be modeled mathematically; that is, for a substance whose crystal structure is known, a set of assumed interatomic potential functions can be used to generate a predicted neutron-scattering spectrum. Comparison of the calculated spectrum with the observed spectrum then enables one to correct or refine the potential functions. A successful investigation confers two main benefits: (1) a set of validated potential functions for the substance investigated, which can then be used to gain insight about chemical behavior or to model more complex systems, and (2) a detailed description of the vibrational dynamics of the substance investigated.

The program described above can be resolved into two major branches--the experimental (acquisition of neutron-scattering spectra) and the computational (generation of calculated spectra and refinement of potential functions). On the experimental side, we have been doing incoherent inelastic neutron scattering with a crystal analyser spectrometer at the Intense Pulse Neutron Source of Argonne National Laboratory. We have studied solid hydrocarbons such as benzene and butane and have recently completed measurements on supercooled water. The latter experiment is significant in that we have succeeded in observing the hydrogen bond dynamics of water. Computationally, we have evolved a rather complex program (LATDYN) which carries out lattice dynamics calculations within the framework of Born-von Karman theory. A number of less ambitious computer codes have been used to study individual molecules and single-chain polymers.

Investigators: Professor S.H. Chen; Messrs. K. Touqan, C. Mizumoto, Ms. S. Cooper.

Support: National Science Foundation.

Related Academic Subject:

22.51 Radiation Interactions and Applications.

Recent References:

S.H. Chen, J. Teixeira and R. Nicklow, "Incoherent Quasielastic Neutron Scattering from Water in Supercooled Regime," Phys. Rev. A26, 3477, (1982).

K. Touqan and S.H. Chen, "Lattice Dynamics of Halogen Crystals," Molec. Phys., 44, 693, (1981).

K. Touqan and S.H. Chen, "An Interatomic Potential Model for Halogen Crystals," Molec. Phys., 47, 457, (1982).

P.A. Egelstaff, J.A. Polo, J.H. Root, L.J. Hanh and S.H. Chen, "Structural Rearrangements in Low-Temperature Heavy Water," Phys. Rev. Lett., 47, 1733, (1981).

### 3.6.3 Kinetic Theory of Dense Fluids and Its Experimental Tests

The study of space- and time-dependent fluctuations in gases and liquids has been a fundamental problem in non-equilibrium statistical mechanics for a number of years. These fluctuations are of interest because they are the basic properties of a many-body system, and they determine the various transport processes that can take place in fluids. In the case of density fluctuations they can be directly measured by thermal neutron and laser light scattering.

A substantial body of literature now exists on theoretical studies using transport equations and mode coupling techniques. There is considerable current interest in problems involving nonlinear behavior in the sense of effects associated with correlated collision events. The problem which we have analyzed in some detail is the Lorentz model of the diffusion of a test particle in a random medium of fixed scatterers. This model exhibits two phases: a low to moderate density phase where particle diffusion behaves like that in a fluid, and a high density phase characterized by particle trapping and absence of diffusion. The mode-coupling theory which we have developed treats both phases as well as the critical point, the percolation density separating the two phases. It appears that this approach can be extended to study fluctuations in fluids at densities approaching structural arrest (freezing). Indeed, interesting results concerning the mechanism of the liquid-glass transition have been obtained recently.

Investigators: Professors S.H. Chen and S. Yip; Dr. E. Leutheusser, Mr. C. Mizumoto, Ms. S. Cooper.

Support: National Science Foundation (January 1979-June 1984). National Science Foundation (proposal pending).

Related Academic Subjects:

22.51 Radiation Interactions and Applications

Recent References:


L. Letamendia, J.P. Chabrat, G. Nouchi, J. Rouch, C. Vaucamps and S.H. Chen, "Light Scattering Studies of Moderately Dense Gas Mixtures I. Hydrodynamic Regime," Physical Review, A24, 1574, (1981).

L. Letamendia, P. Jourbert, J.P. Chabrat, J. Rouch, C. Vaucamps, C. Boley, S. Yip and S.H. Chen, "Light Scattering Studies of Moderately Dense Gases II. Non-Hydrodynamic Regime," Physical Review, A25, 481, (1982).

L. Letamendia, S.H. Chen, J.P. Chabrat, J. Rouch and C. Vaucamps, "Dynamics of Two-Component Gas Mixtures: Effects of Mode Couplings in Rayleigh-Brillouin Spectra," Proc. Eighth Symposium on Thermophysical Properties, Vol. 1, p. 204, Ed. J.V. Sengers, The Am. Soc. Mech. Eng., (1982).

W. Goetze, E. Leutheusser and S. Yip, "Diffusion and Localization in the Two-Dimensional Lorentz Model," Physical Review, A25, 533, (1982).

S. Yip, W.E. Alley and B.J. Alder, "Evaluation of Time Correlation Functions from a Generalized Enskog Equation," Journal of Statistical Physics, 27, 201, (1982).

L. Letamendia, E. Leutheusser and S. Yip, "Modification of a Kinetic Model of the Generalized Enshog Equation," Physical Review, A25, 1222, (1982).

J.P. Boon and S. Yip, "Correlated Dynamics and Light Scattering in Microemulsions," Optica Acta, 29, 1167, (1982).

J. Bosse, E. Leutheusser and S. Yip, "Dynamical Structure Factor of Dense Gases," Physical Review, A27, 1696, (1983).

E. Leutheusser, S. Yip, B.J. Alder and W.E. Alley, "Dynamical Correlations in a Hard-Disk Fluid: Generalized Enskog Theory," Journal of Statistical Physics, 32, 503, (1983).

E. Leutheusser, D.P. Chore and S. Yip, "van Hove Self-Correlation Function of a Hard-Disk Fluid," Journal of Statistical Physics, 32, 523, (1983).

W.E. Alley, B.J. Alder and S. Yip, "The Neutron Scattering Function for Hard Spheres," Physical Review, A27, 3174, (1983).

E. Leutheusser, "Self-Consistent Kinetic Theory for the Lorentz Gas," Physical Review, A28, 1762, (1983).

E. Leutheusser, "Diffusion Blocking in a Frozen Hard Sphere Fluid," Physical Review, A28, 2510, (1983).

J. Ullo and S. Yip, "Molecular Dynamics of Dense Gases: Effects of Continuous Potentials," Physical Review, A29, 2092, (1984).

E. Leutheusser, "Dynamical Model of the Liquid-Glass Transition," Physical Review, A29, 2765, (1984).

### 3.6.4 Atomistic Simulation Studies of Materials Properties and Behavior

The purpose of this project is to develop techniques of discrete-particle simulation and apply them to fundamental problems in materials science. In the case of molecular dynamics simulation, one integrates numerically the Newton's equations of motion for a system composed of typically several hundred atoms and obtains the system properties by appropriate analysis of the resulting atomic positions and velocities. In the case of Monte Carlo simulation, the properties are obtained as ensemble averages over system configurations generated by allowing the atoms to move according to a prescribed transition probability. There are two important advantages of these modeling techniques. First, they enable the macroscopic properties to be directly calculated in terms of atomic structure and inter-atomic forces. Secondly, they provide detailed microscopic information about structure and dynamics that often cannot be obtained by other means, either theoretical or experimental.

Atomistic simulation have no difficulty in dealing with processes that are highly nonlinear, inhomogeneous, nonequilibrium, or strongly coupled. They are therefore particularly effective in problems that are not amenable to analytical studies. Each of the problems that we have studied has this characteristic. The list now includes atomic diffusion in grain-boundary solids, plastic deformation at crack tips, structural transformation and mechanical behavior of stressed solids, nonlinear lattices and kink dynamics, and thermal ignition in exothermically reacting fluids. Problems currently under study are migration kinetics of point defects, high-temperature properties of solids with defects, and molecular vibrations in hydrocarbon liquids.

Investigators: Professor S. Yip; Messrs. D.P. Chou, A. Combs, B. DeCelis, T. Kwok, R. Najafabadi, K. Touqan, F. Carrion, J. Anderson, M. Sabochick, and Ms. C. Nitta.

Support: Army Research Office (1974-1983), National Science Foundation (proposal pending), Department of Energy (proposal pending), Schlumberger Fellowship (1982-), IBM Graduate Fellowship (1983-).

Related Academic Subjects:

22.44J Computational Methods in Materials Science and Engineering
22.71J Physical Metallurgy Principles for Engineers

Recent References:

D.P. Chou and S. Yip, "Computer Molecular Dynamics Simulation of Thermal Ignition in a Self-Heating Slab," Combustion and Flame, 47, 215, (1982).

G.H. Bishop, R.J. Harrison, T. Kwok and S. Yip, "Computer Molecular Dynamics Studies of Grain Boundary Structures: I. Observations of Coupled Sliding and Migration in a Three-Dimensional Simulation," Journal of Applied Physics, 53, 5596, (1982).

G.H. Bishop, R.J. Harrison, T. Kwok and S. Yip, "Computer Molecular Dynamics Studies of Grain Boundary Strutures: II. Migration, Sliding and Annihilation in a Two-Dimensional Solid," Journal of Applied Physics, 53, 5609, (1982).

B. deCelis, A.S. Argon and S. Yip, "Molecular Dynamics Simulation of Crack Tip Processes in Alpha Iron and Copper," Journal of Applied Physics, 54, 4864, (1983).

J.A. Combs and S. Yip, "Single Kink Dynamics in a One-Dimensional Atomic Chain," Physical Review, B28, 6873 (1983).

F. Carrion, G. Kalonji and S. Yip, "Evidence for Grain Boundary Phase Transition in a 2D Bicrystal," Scripta Metallurgica, 17, 915, (1983).

R. Najafabadi and S. Yip, "Observation of Finite-Temperature Bain Transformation (fcc→bcc) in Monte Carlo Simulation of Iron," Scripta Metallurgica, 17, 1199, (1983).

J.A. Combs and S. Yip, "Molecular Dynamics Study of Lattice Kink Diffusion," Physical Review, B29, 438, (1984).

A.J.C. Ladd et al., "Grain Boundary Free Energy of a Two-Dimensional Bicrystal," Physics Letters, 100A, 195, (1984).

R. Najafabadi and S. Yip, "Mechanical Response of a Stressed Two-Dimensional Bicrystal," Scripta Metallurgica, 18, 159, (1984).

T. Kwok, P.S. Ho and S. Yip, "Molecular Dynamics Studies of Grain Boundary Diffusion: I. Structural Properties and Mobility of Point Defects," Physical Review, B29, 5354, (1984).

T. Kwok, P.S. Ho and S. Yip, "Molecular Dynamics Studies of Grain Boundary Diffusion: II. Vacancy Migration Diffusion Mechanism and Kinetics," Physical Review, B29, 5363, (1984).

### 3.6.5 Quasielastic Light Scattering Studies of Motility of Cells and Aggregation of Macromolecules

A new technique for determining the Doppler frequency shifts in the scattered laser light from slowly moving particles has been developed. This so-called "photon correlation spectroscopy" is a completely digital technique in the time domain whereby the intensity correlation function of the scattered light $\langle I(t+\tau)\rangle$ can be simultaneously measured at 256 values of the delay time $\tau$ by using a delay coincidence method. The accessible range for $\tau$ in this instrument is from 1 sec to 1 $\mu$sec which covers a useful range of fluctuation phenomena from neutron population in a reactor core to flow of particles in turbulent fluids. The method has been applied to the study of slow fluctuations of the concentration in a binary liquid mixture near the critical point with a great deal of success. Recently this technique has been applied to measurement of isotropic random motion of bacteria in liquid media and also to directed biased motions when a chemotactic agent is present. The usefulness of the method for study of macromolecular aggregation kinetics in solution has also been demonstrated.

Investigators: S.H. Chen, Ms. D. Bendedouch, Ms. S. Cooper, Messrs. Y.S. Chao, C.L. Lin, M. Kotlarchyk, C. Mizumoto, and E. Sheu.

Support: National Science Foundation (Biophysics Section), (Feb. 1979-July 1984). Petroleum Research Fund of the American Chemical Society (1982-1985).

Related Academic Subjects:

22.51 Radiation Interactions and Applications
8.442 Statistical Optics and Spectroscopy

Recent References:

P.C. Wang and S.H. Chen, "Quasi-elastic Light Scattering from Migrating Chemotactic Bands of E. coli II: Analysis of Anisotropic Bacterial Motions," Biophys. J., (1981).

W.J. Glantschnig and S.H. Chen, "Light Scattering from Water Droplets in the Geometrical Optics Approximation," Appl. Opt., 20, 2499, (1981).

S.H. Chen, B. Chu, R. Nossal, Eds., Scattering Techniques Applied to Supramolecular and Nonequilibrium Systems, NATO ASI Series B: Physics, Vol. 73, Plenum Press, New York, (1981).

R.E. Tanner, B. Berpigny, S.H. Chen and C. Rha, "Conformational Change of Protein/SDS Complexes in Solution--A Study by Dynamic Light Scattering," J. Chem. Phys., 76, 3866, (1982).

S.H. Chen and F.R. Hallett, "Determination of Motile Behavior of Prokaryotic and Eukaryotic Cells by Quasielastic Light Scattering," Quart. Rev. Biophys., 15, 1, (1982).

S.H. Chen, C.C. Lai, J. Rouch and P. Tartaglia, "Probability Distribution of Photocounts of the Light Scattered by Critical Fluctuations," J. Stat. Phys., 30, 699, (1983).

### 3.6.6 Small Angle Neutron Scattering Studies of Structure and Interaction of Micelles, Microemulsions and Proteins

A new method of extracting the intermicellar structure factor for strongly interacting ionic micelles using SANS technique has been developed. The method has been applied to small lithium dodecyl sulfate micelles in both dilute and concentrated solutions. We were able to extract both the aggregation number of the micelle and its surface charge at all concentrations with good accuracy. A contrast variation method, which takes advantage of the large difference between scattering lengths of hydrogen and deuterium atoms, has also been used to study in detail the internal structure of small micelles.

Studies have been made of the recently found critical phenomena in a three-component microemulsion, AOT (a surfactant, sodium di-2-ethyl-hexylsulfosuccinate) + n-decane + water, system. The main interest is in determining the nature of the critical point and its associated order parameter. Our SANS results have been analyzed by assuming critical concentration fluctuations of polydispersed microemulsion droplets. We obtained non-Ising-like values for the exponents and , while the size of the microemulsion droplets remains constant with 30 percent polydispersity. Recently, structure of dense phases has also been determined.

Globular protein bovine serum albumin in solutions of different pH values have been studied. By varying the pH one can vary the surface charge of the protein and can thus vary the strength of interactions between protein molecules. We were able to determine the shape and size of the protein, its bound water content, and also the surface charge. Interesting ordering phenomena have been seen at high protein concentrations.

Investigators: Professor S.H. Chen; Ms. D. Bendedouch, Ms. S. Cooper, Messrs. Y.S. Chao, C.L. Lin, M. Kotlarchyk, C. Mizumoto, E. Sheu.

Support: National Science Foundation (Biophysics Section), (Feb. 1979-July 1984). Petroleum Research Fund of the American Chemical Society (1982-1985).

Related Academic Subjects:

22.51 Radiation Interactions and Applications
8.442 Statistical Optics and Spectroscopy

Recent References

D. Bendedouch, S.H. Chen and W.C. Koehler, "Structure of Ionic Micelles from Small Angle Scattering," J. Phys. Chem., 87, 153, (1983).

D. Bendedouch, S.H. Chen and W.C. Koehler, "Determination of Interparticle Structure Factors in Ionic Micellar Solutions by Small Angle Neutron Scattering," J. Phys. Chem., 87, 2621, (1983).

D. Bendedouch and S.H. Chen, "Structure and Interparticle Interactions of Bovine Serum Albumin in Solution Studied by Small Angle Neutron Scattering," J. Phys. Chem., 87, 1473, (1983).

D. Bendedouch and S.H. Chen, "Study of Intermicellar Interaction and Structure by Small Angle Neutron Scattering," J. Phys. Chem., 87, 1653, (1983).

M. Kotlarchyk, S.H. Chen and J.S. Huang, "Temperature Dependence of Size and Polydispersity in a Three-Component Microemulsion by Small Angle Neutron Scattering," J. Phys. Chem., 86, 3273, (1982).

M. Kotlarchyk, S.H. Chen and J.S. Huang, "Critical Behavior of a Microemulsion Studied by Small Angle Neutron Scattering," Phys. Rev. A28, 508, (1983).

M. Kotlarchyk and S.H. Chen, "Analysis of Small Angle Neutron Scattering Spectra from Polydisperse Interacting Colloids," J. Chem. Phys., 79, 2461, (1983).

D. Bendedouch and S.H. Chen, "Effects of an Attractive Potential on Interparticle Structure of Ionic Micelles at High Salt Concentration," J. Phys. Chem. (to appear in 1984).

M. Kotlarchyk, S.H. Chen, J.S. Huang and M.W. Kim, "Structure of Three-Component Microemulsions in the Critical Region Determined by Small Angle Neutron Scattering," Phys. Rev. A. (to appear in 1984).

S.H. Chen and D. Bendedouch, "Structure and Interactions of Proteins in Solution Studied by Small Angle Neutron Scattering," an article to appear in Enzyme Structure, a volume of Methods in Enzymology, edited by H.S. Hirs and S.N. Timasheff, Academic Press.

## 3.7 Biological and Medical Applications of Radiation and Radioisotopes

This field encompasses the general study of radiation production and interaction as applied to biological and medical applications. Includes various aspects of medical diagnosis including medical imaging as well as various aspects of radiation therapy including neutron capture therapy. Research opportunities exist at MIT and in the teaching hospitals.

### 3.7.1 Subjects of Instruction

The basic subjects of instruction in this area include the undergraduate subject 22.04, Radiation Effects and Uses, and the graduate subjects 22.55J, Biological and Medical Applications of Radiation and Radioisotopes, and 22.56J, Principles of Medical Imaging.

22.04: Radiation Effects and Uses, this course covers a wide range of material concerning ionizing radiation, its origins, uses and hazards. Tours through facilities such as the MIT nuclear reactor, fusion center, positron camera lab, electron microscope lab and Harvard cyclotron lab are integral to the course. Lectures include discussions on the history of radiation research, cosmic rays, nuclear power and weapons, detection methods and medical applications.

22.55J: Biological and Medical Applications of Radiation and Radioisotopes, covers the principles of radiation production and interactions. Radiation dosimetry with emphasis on applications and health hazards. Shielding of beta, gamma, and neutron radiation from isotope and machine sources. Detection and spectroscopy of beta, gamma, and neutron radiation. Neutron activation analysis. Production of radioisotopes and radiopharmaceuticals. Principles of nuclear medicine. Requires a comprehensive term paper and presentation.

22.56J: Principles of Medical Imaging, This course covers a broad range of topics in Medical Imaging, including X-ray, nuclear medicine, ultrasound, NMR, emission and transmission computed tomography, and other modalities.

Two-dimensional and three-dimensional imaging techniques and displays. Fundamentals of image formation, physiology of image perception, physics of radiation and ultrasound interaction and detection, and physics of NMR. Quantitation of images and reconstruction algorithms. Medical applications, biological hazards, and cost-benefit analysis of imaging modalities. A comprehensive term paper required.

### 3.7.2 Boron Neutron Capture Therapy

A program of preclinical study of BNCT continues. Studies are aimed at the development of track etch techniques for determining the distribution of boron compounds in tissue. The studies also include the dosimetry of boron capture and other radiation, development of new boron compounds and improvement in radiation sources.

Investigators: Professor G.L. Brownell; Mr. J. Kirsch and Dr. J. Fox (Division of Comparative Medicine, MIT).

Support: National Institutes of Health

Related Academic Subject:

22.55J Biological and Medical Applications of Radiation and Radioisotopes.

Recent References:

J.E. Kirsch and G.L. Brownell, "Improved Methods of Neutron-Induced Track Etch Autoradiography," Proceedings on the 1st International Symposium on Neutron Capture Therapy, pp. 164-173, October 12-14, 1984.

M. Ashtari, G.L. Brownell and M. Forrest, "Preliminary Dosimetry Studies of the MIT Reactor (MITR-II) Medical Facility," Proceedings of the 1st International Symposium on Neutron Capture Therapy, pp. 88-98, October 12-14, 1983.

G.L. Brownell, J.E. Kirsch, J.C. Murphy, M. Ashtari, W.C. Schoene, C. Rumbaugh and G.R. Wellum, "Pre-Clinical Neutron Capture Therapy Trials at MIT using Na B H SH," Proceedings of the 1st International Symposium on Neutron Capture Therapy, pp. 304-314, October 12-14, 1983.

### 3.7.3 Collaborative Projects with MGH

Medical imaging is an area of increasing interest in diagnostic medicine. In collaboration with the MGH, programs are being developed in the area of positron tomography. The program involves development of new tomographic instruments having high resolution, development of new compounds and biological and medical study.

A study will commence shortly on the analysis of systems for highly automated production of radiopharmaceuticals. Such a system may result in a much wider application of positron imaging.

NMR imaging is playing an increasingly important role and a number of various groups are interested in developing new and improved instruments. This topic is being included in future imaging courses.

Investigators: Professor G.L. Brownell; Mr. John Kirsch

Support: National Institutes of Health; U.S. Department of Energy

Related Academic Subjects:

22.56J Principles of Medical Imaging

Recent References:

G.L. Brownell, T.F. Budinger, P.C. Lauterbur and P.L. McGeer, "Positron Tomography and Nuclear Magnetic Resonance Imaging," Science, 215, 619-626, (1982).

G.L. Brownell, C.A. Burnham, D.A. Chesler, J. Bradshaw, D. Kaufman, and S. Weise, "PCR-I - High Resolution Positron Tomography Using Analog Coding," IEEE Transactions on Medical Imaging, (1983).

A.-L. Kairento, G.L. Brownell, C.J. Schluederberg and D.R. Elmaleh, "Regional Blood-Flow Measurement in Rabbit Soft-Tissue Tumor with Positron Imaging Using the Cl O  Steady-State and Labeled Microspheres," J. Nucl. Med. 24: 1135-1142, (1983).

## 3.8 Radiological Sciences

Radiological science covers the general field of radiation and radioisotope applications in biology and medicine. The field includes radiation biophysics, diagnostic techniques including medical imaging, radiation therapy and some aspects of radiopharmaceutical chemistry. Research in this field is rapidly expanding and interfaces with a growing and important area of health care. Research opportunities exist at MIT and at the teaching hospitals.

### 3.8.1 Subjects of Instruction

The basic subjects of instruction in the radiological sciences field include the undergraduate subject 22.04, Radiation Effects and Uses, and the two graduate subjects, 22.56J, Principles of Medical Imaging, and 22.57J, Radiation Biophysics.

22.04: Radiation Effects and Uses, this course covers a wide range of material concerning ionizing radiation, its origins, uses and hazards. Tours through facilities such as the MIT nuclear reactor, fusion center, positron camera lab, electron microscope lab and Harvard cyclotron lab are integral to the course. Lectures include discussions on the history of radiation research, cosmic rays, nuclear power and weapons, detection methods and medical applications.

22.56J: Principles of Medical Imaging, this course covers a broad range of topics in Medical Imaging, including X-ray, nuclear medicine, ultrasound, NMR, emission and transmission computed tomography, and other modalities. Two-dimensional and three-dimensional imaging techniques and displays. Fundamentals of image formation, physiology of image perception, physics of radiation and ultrasound interaction and detection and physics of NMR. Quantitation of images and reconstruction algorithms. Medical applications, biological hazards, and cost-benefit analysis of imaging modalities. A comprehensive term paper required.

22.57J: Radiation Biophysics, covers radiobiology, *in vivo* models for radiation effects on tumors, mathematical models of cell survival, radiation chemistry, diagnostic radiology and radiation therapy. The contents of this course evolve as new information becomes available for analysis.

### 3.8.2 Tumor Strangulation

Studies are being conducted on the effects of ionizing radiation on tumor vasculature. A novel approach of plastic injection into treated tumor vasculature and subsequent analysis under high resolution scanning electron microscopy has been developed. The results provide new insights into tumor treatment and into the mechanisms of tumor growth.

Investigator: Professor Alan C. Nelson

Related Academic Subjects:

22.04 Radiation Effects and Uses
22.55J Biological and Medical Applications of Radiation and Radioisotopes
22.57J Radiation Biophysics

Support: Whitaker Health Sciences Fund, National Heart, Lung and Blood Institute, and the Athwin Foundation.

Recent References:

S. Kochi, et al., *Structure of Ocular Vessels*, Igaku-Hoin Press, NY (1978).

A. Shah, "Analysis of Tumor Vasculature and Radiation Effects," Ph.D. Thesis, Department of Nuclear Engineering, MIT, (1983).

### 3.8.3 Magnetic Field Effects on Biomaterials

Basic research on the effects of high magnetic fields and high field gradients on biological materials is being conducted at the Francis Bitter Magnetic Lab and the Whitaker College Laboratory of Microscopy. Current interests focus on the orientation of fibrin fibres and collagen fibres in magnetic fields with a view to the synthesis of new high strength biomaterials for use in artificial skin, for example. Magnetic field effects on living cells is also being examined.

Investigators: Dr. R.B. Frankel and Professor A.C. Nelson.

Related Academic Subjects:

22.111 Nuclear Physics for Engineers I
22.51 Radiation Interactions and Applications

Support: Office of Naval Research

Recent References:

J. Torbet, et al., "Oriented Fibrin Gels Formed by Polymerization in Strong Magnetic Fields," Nature, 289, 91, (1981).

### 3.8.4 Microstructural Cell Damage Due to Heavy Ion Radiation

This is a continuation of research in conjunction with the Lawrence Berkeley Laboratory where irradiations with heavy ion beams are accomplished on cyclotron and synchrotron accelerators. We are studying damage to cell membranes and cytoplasm with scanning microscopy.

Investigators: Professor A.C. Nelson.

Related Academic Subjects

22.04 Radiation Effects and Uses
22.51 Radiation Interactions and Applications
22.55J Biological and Medical Applications of Radiation and Radioisotopes
22.57J Radiation Biophysics

Support: Lawrence Berkeley Laboratory.

Recent References:

A.C. Nelson, "Theoretical and Observational Analysis of Individual Ionizing Particle Effects in Biological Tissues," Ph.D. Thesis, Univ. of California, Berkeley, Department of Biophysics, (1980).

A. Ben-Ze'ev, et al., "The Outer Boundary of the Cytoskelton," Cell, 17, p. 859, (August 1979).

### 3.8.5 Image Science and Technology

Research in the area of image formation in electron microscopy is aimed at obtaining information using newly developed technologies. These studies emphasize hardware development and image analysis including quantitation, standardization, feature extraction, and automated collection. These new technologies facilitate research in radiology and materials science.

Investigators: Professor A.C. Nelson, Dr. L. Sher and Mr. D.C. Cummings.

Related Academic Subjects:

22.04 Radiation Effects and Uses
22.57J Radiation Biophysics
22.56J Principles of Medical Imaging

Support: Whitaker Health Sciences Fund, Sloan Foundation, Athwin Foundation, Ginisco Corp., National Cancer Institute, National Heart, Lung and Blood Institute.

## 3.9 Health Radiation Physics

The Health Radiation Physics Program is designed to provide students with a strong foundation in the scientific and engineering disciplines needed for the management and control of irradiation exposures. It emphasizes principles of radiobiology, radiation measurement and dosimetry, risk assessment, and management of radiation exposure.

### 3.9.1 Subjects of Instruction

The following subjects are offered to students specializing in the area of health radiation physics.

22.111: Nuclear Physics for Engineers I, deals with basic nuclear physics for advanced students majoring in engineering. Basic properties of nucleus and nuclear radiation. Quantum mechanical calculation of bound states and transmission coefficients. Nuclear force and nuclear shell model. Nuclear binding energy and stability. Interaction of charged particles, neutrons, gammas with matter. Nuclear decays. Introductory nuclear reactions.

22.29: Nuclear Measurements Laboratory, covers basic principles of interaction of nuclear radiations with matter. Principles underlying instrumental methods for detection and energy determination of gamma-rays, neutrons and charged particles are discussed. Other topics include applications to applied radiation physics, health physics, and reactor technology; laboratory experiments on gas-filled, scintillation and semiconductor detectors; nuclear electronics such as pulse amplifiers, multi-channel analyzers and coincidence techniques; applications to neutron activation analysis, X-ray fluorescence analysis, thermal neutron cross sections, and radiation dosimetry.

22.37: Environmental Impacts of Electricity, assesses the various environmental impacts of producing thermal and electric power with currently available technology. Compares impacts throughout both the fossil and nuclear fuel cycles. Topics include fuel resources and extraction, power station effluents, waste heat disposal, reactor safety, and radioactive waste disposal.

22.39: Nuclear Reactor Operations and Safety, deals with the principles of operating nuclear reactor systems in a safe and effective manner. Emphasizes light water reactor systems with transient response studies including degraded core recognition and mitigation. Other topics include: consequence analysis and risk assessment; lessons from past accident experience; NRC licensing and regulations. Demonstrations include operation of the MIT Research Reactor and the use of a PWR concept simulator. An optional lab section is available.

22.51: Radiation Interactions and Applications, deals with the basic priniples of interaction of electromagnetic radiation, thermal neutrons, and charged particles with matter. Introduction to classical electrodynamics, quantum theory of radiation field and time-dependent perturbation theory. Emphasis is on the development of transition probabilities and cross sections describing interaction of various radiations with atomic systems. Applications include emission and absorption of light, theory of gas lasers, Rayleigh, Brillouin, and Raman scattering, X-ray diffraction, photoelectric effect, Compton scattering, Bremsstrahlung, and interaction of intense light with plasma. The last part deals with use of thermal neutron scattering as a tool in condensed matter research.

22.55J: Biological and Medical Applications of Radiation and Radioisotopes, covers the principles of radiation production and interactions. Radiation dosimetry with emphasis on applications and health hazards. Shielding of beta, gamma and neutron radiation from isotope and machine sources. Detection and spectroscopy of beta, gamma, and neutron radiation. Neutron activation analysis. Production of radioisotopes and radiopharmaceuticals. Principles of nuclear medicine. Requires a comprehensive term paper and presentation.

22.57J: Radiation Biophysics, covers radiobiology, *in vivo* models for radiation effects on tumors, mathematical models of cell survival, radiation chemistry, diagnostic radiology and radiation therapy. The contents of this course evolve as new information becomes available for analysis.

22.58: Health Physics II, uses the 5 MW MIT Research Reactor extensively to provide students with real experience in radiation measurement, management, and control. Other facilities include a cyclotron, linear accelerator, and power reactors. Reviews applicable standards for radiation exposure. Covers theory and use of , , , and n detectors and spectrometers. Covers preparation and handling of isotopes, shielding, analysis and design of radiation protection systems and procedures, in applications including nuclear power generation, medical and research uses of radiation.

### 3.9.2 Control of Argon-41 at the MIT Research Reactor

This research is designed to identify, quantify and mitigate the sources of argon-41 emitted from the MIT Research Reactor.

Investigators: Professor O.K. Harling; Messrs. L. Clark, Jr. and John Deplitch.

Support: U.S. Army and MIT Nuclear Reactor Laboratory.

### 3.9.3 Improved Methods to Remove Radon-222 and Its Decay Products from Indoor Air.

Radon-222 and its daughter products cause a major part of the normal background radiation exposure to the general population. In some cases the radiation exposure from this source greatly exceeds normal background and in some buildings reaches dangerously high levels. According to recent publications, ten thousand excess fatal lung cancers may result from this source each year in the USA.

This research involves the development of improved technology for removal of Radon from indoor air. Emphasis in this work will be placed on electrostatic precipitator development.

Investigators: Professor O.K. Harling; Dr. Dade W. Moeller, Harvard School of Public Health and Mr. Claudio Rubio.

Support: Chilean Atomic Energy Commission, MIT Nuclear Reactor Lab and Florida Institute of Phosphate Research.

## 3.10 Quantum Thermodynamics

Professors Elias P. Gyftopoulos and Gian Paolo Beretta of the Mechanical Engineering Department continued their research on the foundations of quantum thermodynamics. The emphasis of this research has been on the general equation of motion of quantum thermodynamics and mathematical forms that distinguish between quantal and nonquantal uncertainties. Significant progress was made in both these efforts. A nonlinear quantum equation of motion was conceived that satisfies the requirements of: (a) energy conservation; (b) nondecrease of entropy; and (c) leading from a non-equilibrium to a thermodynamic equilibrium state.

The possibility of critical experiments that distinguish between reducible and irreducible mixed quantum states is being investigated.

### 3.10.1 Subjects of Instruction

22.571J: General Thermodynamics I, presents the foundations of thermodynamics in a general way, followed by the application of thermodynamic principles to energy conversion systems and industrial processes. First part: the first and second laws are introduced together with the definitions of work, energy, stable equilibrium, available work, entropy, thermodynamic potentials, and interactions (work, non-work, heat, mass transfer). Second part: thermodynamic analyses of stable equilibrium properties of materials, bulk flow, energy conversion processes, chemical equilibria, combustion, and industrial manufacturing processes.

22.572J: Quantum Thermodynamics, presents a nonstatistical unified quantum theory of mechanics and thermodynamics for all systems, including a single particle, and all states, including nonequilibrium, and an equation of motion for reversible and irreversible processes. Self-contained review of necessary background. Applications to fermious, bosons, black-body radiation, electrons in metals, crystals, rate processes, and relaxation phenomena.

## 3.11 Energy: Policy and Environmental Issues

Full development of the Department's original and still prime role in applications of nuclear technology (fission, fusion and other radiation-related disciplines) brings us into the areas of energy policy, environmental effects, national and international affairs, studies of the overall health of the nuclear and related sectors, power plant siting policies, regulatory procedures, and a number of fundamental issues that underlie how modern civilizations handle their problems.

These activities have continued during the past year and have had substantial influence both at MIT and elsewhere.

### 3.11.1 Subjects of Instruction

The basic subjects of instruction in the energy field include the undergraduate subject 22.08, Energy, and the two graduate subjects 22.341, Nuclear Energy Economics and Policy Analysis, and 22.81, Energy Assessment.

22.08: Energy, this subject deals with energy from a holistic point of view: provision, rational utilization and conservation, regulation, environmental effects, and impact on other societal sectors. Resources of petroleum, natural gas, coal, nuclear and other energy forms. Technologies of providing energy from these forms. Utilization of energy in various sectors: transportation, industrial, commercial, and domestic, including especially opportunities for increased efficiency and energy conservation. Regulatory, tax, and other institutional arrangements that effect production and use patterns. Environmental costs and opportunities associated with exercising various energy strategies, both existing and proposed. Domestic and international political, strategic, and economic implications. Meets with 22.81, but some assignments differ.

22.085: Introduction to Technology and Law, introduces the basic principles and functions of law, using legal cases and materials arising from scientific and technical issues. Provides an understanding of the law and legal processes as they impact upon the work of engineers and scientists. Study of judicial law making focuses on elementary civil procedure and how change in legal doctrine takes place. Examination of statutory law making shows how federal and state power to govern grows as technology grows. Administrative law making focuses on the regulatory agencies' role in controlling and supporting technology as well as the extent and curbs on their power. Study of law cases, using so-called "Socratic method," and of legal processes and doctrines provides insight into the lawyer's working methods. Law's task of resolving conflicts found in scientific and engineering alternatives sensitizes students to choice of values questions.

22.341: Nuclear Engineering Economics and Policy Analysis, presents a comprehensive assessment of the economic, environmental, political and social applications of the principles of engineering economics; comparison of alternatives using discounted cash flow methods. Technology assessment/-policy analysis of institutional alternatives for R&D, management and regulation; includes nuclear power plant licensing, nuclear waste management, and nuclear power and weapons proliferation.

22.37: Environmental Impacts of Electricity, assesses the various environmental impacts of producing thermal and electric power with currently available technology. Compares impacts throughout both the fossil and nuclear fuel cycles. Topics include fuel resources and extraction, power station effluents, waste heat disposal, reactor safety, and radioactive waste disposal.

22.38: Reliability Analysis Methods, covers the methods of reliability analyses including fault trees, decision trees, and reliability block diagrams. Discusses the techniques for developing the logic diagrams for reliability assessment, the mathematical techniques for analyzing them, and statistical analysis of required experience data. Practical examples of their application to the risk assessment of nuclear power reactors and other industrial operations discussed.

22.81: Energy Assessment, is an introduction to the broad field of energy, including technological, social, environmental, economic, and political aspects. Energy provision, transformation, and utilization. Development of energy options for the future, and analyses of present regional, national, and international energy programs. Intended for graduate students entering energy fields in which energy is important, and who desire a holistic overview.

22.85J: Case Studies in Energy, Technology, Economics and Management, gives students with diverse backgrounds an opportunity to study the multi-dimensional (i.e., technological, economic and enviromental) nature of complex energy issues in a concrete context. Class is divided into working groups for specific case studies. Investigates one or more topics of current interest involving fossil fuel, nuclear, and renewable energy sources.

22.913: Graduate Seminar in Energy Assessment, is primarily designed as a communication medium among students conducting research in energy related areas, and as a means for obtaining critical evaluation of their ongoing research work. Covers topics ranging from technological comparisons to environmental, social, resource, and political impacts, depending on current student and faculty interest.

### 3.11.2 Energy Supply and Demand Implications of CO

Climatologists predict that if the present global, long-term trend toward increased use of fossil fuels continues, the buildup of carbon dioxide in the atmosphere will cause large changes in global climate, perhaps by the middle of the next century. Long lead-times to affect large-scale global technologies requires that energy options designed to ameliorate this problem be studied now. We have studied this problem, made new assessments of energy technologies likely to be available, and combined them with a global energy model developed by the Institute for Energy Analysis. The model combines resources and technological and economic considerations for different sectors and regions. The principal conclusion is that "$CO_2$-benign" strategies are available that appear both technologically and economically attractive. The most effective of these involves increasing the effectiveness of energy use, nuclear power, renewables and the continuing shift toward electric power use can also play large roles, especially if the full societal cost of using coal is taken into account. Consideration was given to the problem of discounting far-future costs and benefits and to institutional arrangements that could help to develop international consensus. Some of the work was carried out in collaboration with Stanford University.

Investigators: Professor D.J. Rose; Dr. M.M. Miller, Dr. C. Hill (Center for Policy Alternatives); Prof. C. Agnew (Stanford Univ.); Messrs. J. Pransky and P. Poole.

Support: National Science Foundation.

Related Academic Subjects:

22.81 Energy Assessment

Recent References:

A.M. Perry, K.J. Araj, W. Fulkerson, D.J. Rose, M.M. Miller, R.M. Rotty, "Energy Supply and Demand Implications of $CO_2$," Energy, 7, 991-1004, (December 1982).

D.J. Rose, M.M. Miller and C. Agnew, "Global Energy Futures and $CO_2$-induced Climate Change," MIT Report No. MIT-EL 83-015. Also MITNE-259, (November 1983).

D.J. Rose, M.M. Miller and C. Agnew, "Reducing the Problem of Global Warming," Technology Review, pp. 47-58 (May/June 1984).

### 3.11.3 International Nuclear Relations

International trade in nuclear equipment, materials and technology is essential for the preservation and expansion of nuclear power's contribution to world energy supplies. The conduct of this trade is complicated by the need to ensure that the goods and services involved are being used exclusively for civilian purposes. The goal of creating a trading regime which maximizes the separation of peaceful and military nuclear activities has been assigned a high priority by the U.S. government since the outset of the nuclear era. Political and diplomatic developments in this field have had an important impact on the direction taken by nuclear power programs during these years. Conversely, technical and economic developments in nuclear power generation have strongly influenced the nonproliferation policy agenda.

Research on these relationships has continued during the last two years. The recent focus of these efforts has been on the implications for international nuclear trade and the nonproliferation regime of fundamental changes that are taking place in the structure of the world nuclear supply industry. The situation in the Pacific Basin region is representative: while Japan, South Korea, and Taiwan continue to develop their nuclear industries, productive capacity in the United States is eroding. These structural trends could transform civil nuclear relations both in the region and beyond.

Investigators: Professor R.K. Lester.

Support: Japanese Ministry of Foreign Affairs through MIT Center for International Studies.

Related Academic Subjects:

| | |
|---|---|
| 22.76J | Introduction to Nuclear Chemical Engineering |
| 22.81 | Energy Assessment |
| 22.341 | Nuclear Energy Economics and Policy Analysis |
| 17.841 | The Technology and Politics of Nuclear Weapons and Arms Control |

Recent References

R.K. Lester, "Nuclear Energy Interdependence and the American Nuclear Energy Crisis," OPEC Review, V(2), Summer 1981, 72-94.

R.K. Lester, "U.S.-Japanese Nuclear Relations: Structural Change and Political Strain," Asian Survey, Vol. XXII, No. 5, May 1982, 417-433.

R.K. Lester, "Foreign Policy Preaching and Domestic Practice," Society, Vol. 20, No. 6, 48-52, (September/October 1983).

R.K. Lester, "Structural Change in the Nuclear Power Plant Industry in the Pacific Basin Region," Columbia Journal of World Business, (1983).

### 3.11.4 Nuclear Waste Management Technology

The outlook for civil nuclear power in the United States and several other countries throughout the world is closely linked to the resolution of problems at the back-end of the nuclear fuel cycle, including, especially, the management and disposal of nuclear wastes. The successful performance of mined geologic repositories for final disposal of reprocessed high level wastes or spent fuel is of central importance to the overall effectiveness of the national nuclear waste management program. Analysis of the thermomechanical and thermo-hydrological behavior of the host rock medium is a key element of waste repository design. Recent efforts in this area have included the development of models to predict the near-field temperature distribution and far-field temperature, stress and displacement profiles in waste repository host rock. Other models have been developed to assess the economic consequences of storing the high-level waste in engineered surface facilities for an extended period of cooling prior to final disposal.

Other research projects carried out during the last two years in the waste management field have included a safety assessment of uranium mill tailings disposal methods, an economic analysis of alternative volume reduction systems for low-level waste from power reactors and leaching studies of low-level waste forms.

Investigators: Professor R.K. Lester.

Support: U.S. Department of Energy.

Related Academic Subjects:

| | |
|---|---|
| 22.77 | Nuclear Waste Management |
| 22.76J | Intoduction to Nuclear Chemical Engineering |
| 22.341 | Nuclear Energy Economics and Policy Analysis |

Recent References:

Malbrain, C., R.K. Lester and J.M. Deutch, "Analytical Approximations for Long-Term Decay Behavior of Spent Fuel and High-Level Waste," Nuclear Technology, Vol. 57, 292-305, (May 1982).

R.K. Lester, "Nuclear Waste Management: Some Considerations of Scale," Radiation Research, 91, 1-21, (1982).

Malbrain, C. and R.K. Lester, "Impact of Thermal Constraints on the Optimal Design of High-Level Waste Repositories in Geologic Media," Nuclear Engineering and Design, 73, 331-341, (1982).

S.M. Reilly, "Radiation Damage to Cation, Anion, and Mixed Bed Ion Exchange Resins," SB Thesis, Department of Nuclear Engineering, MIT, 1983.

J. Lee, "Economic Evaluation of Low-Level Radioactive Waste Volume Reduction Systems," Nuclear Engineer Thesis, Department of Nuclear Engineering, MIT, (1983).

S.R. Allen, "A Technical Assessment of Uranium Mill Tailings Management," Nuclear Engineer Thesis, Department of Nuclear Engineering, MIT, (1984).

## 3.12 Nuclear Power Plant Innovation Project

A broad range of plausible scenarios can be postulated under which nuclear power may again be called on to provide an important fraction of the nation's new and replacement energy supplies by the turn of the century. A major new program of research on advanced designs for nuclear power plant systems targeted for commercial introduction in the 1990s has been initiated.

A feasibility study was undertaken in 1983 with the objectives of (1) assessing the possible role of nuclear power plant design innovations in enhancing the attractiveness of the nuclear energy option to U.S. utilities, (2) identifying the most promising avenues for further technological development, and (3) defining a role for MIT in the context of such efforts.

Significant opportunities exist for design innovations which would reduce the demands placed on plant builders and operators, or which would enhance the attractiveness of nuclear power to utilities in other ways.

Based on the results of the feasibility study, a multi-year research program has been developed. The program will be centered on engineering development projects in two areas: evolutionary improvements in light water reactor (LWR) designs; and small, modular high temperature gas reactor systems. The third element will consist of supporting engineering, social science, and institutional and policy studies. The three program elements are described in more detail in the following sections. The program is based in the Nuclear Engineering Department, but will draw on a broad range of relevant interests and experience at MIT.

### 3.12.1 The Light Water Reactor (LWR) Innovation Project

The LWR Innovation Project is focused upon the contributions which LWR technology innovation can make in the revitalization of nuclear power in the United States. A principal component of this effort is a project to refine the design goals of the next generation of Light Water Reactors, with emphasis upon achieving improvements in capacity factor and reduction of the construction duration.

The motivation of this overall effort is to prevent the nuclear option from being lost unnecessarily through being available only in uneconomic configurations. In considering how to advance this effort we have focused upon refinement of the designs of new reactors because this is the area where the greatest opportunities for improvements exist. It is also the area where the greatest contributions could be made by the group at MIT which would be involved in this project. Importantly, we have not focused our project upon improvements in existing nuclear power stations because substantial resources are being devoted to this area currently, because our efforts would not be likely to change significantly the improvements which will be achieved and because the range of possible design modifications in this area is limited. However, we recognize that these improvements will also be valuable to the current generation of power stations.

We have concluded (with perfect hindsight) that in addition to non-technical factors many of the problems of the current generation of power stations could have been prevented through use of a more comprehensively formulated design goal. Such a formulation would involve identifying the attributes necessary for maximizing the economic performance of the plant. It would involve roughly uniform reconsideration of the functions of all portions of the plant, in contrast to the current pattern of a decreasing devotion to design resources as one moves out from the reactor core. We intend to use the experience of the current generation of plants to improve the designs of the next generation. The major technical areas of potential improvements involve simplification, reliability improvements, refinement of safety requirements and design for rapid construction, maintenance and repair.

It is our hope that the design group centered at MIT would serve as a catalyst for the nuclear industry in advancing such improvements. We propose a project--centered at MIT but involving a consortium of leading nuclear utilities--which would refine the design goal which the next generation of LWRs would satisfy. In doing this the complete set of essential performance requirements of these plants would be stated explicitly, in a practical form, and with sufficient supporting analyses to demonstrate that at least one solution for meeting each requirement would exist. The design goal is the statement of the performance attributes desired in the plant, and is distinguished from the plant design specification. The design specification consists of the detailed instructions to potential project bidders for supply of systems and components. The design specification is based upon the design goal but carries it to a much finer level of detail, and includes much additional material. The translation of the design goal to a project specification and its satisfaction by plant project designers would remain beyond the scope of this project.

The project would also involve efforts focused upon specific design refinements utilizing a set of parallel approaches to plant improvement. These parallel approaches are summarized in Table 1, in addition to the former elements of the project structure.

As envisioned the project would have a total duration of five years divided into three phases:

1. The project definition phase (one year) - consisting of work upon a small set of high priority projects (see Table 1) and a survey of the important operational problems of LWRs worldwide.

2. The preliminary design goal definition phase (two years) - consisting of individual investigations for practical formulation of a preliminary design goal.

3. The final design goal definition phase (two years) - consisting of transmittal of the preliminary design goal to the consortium utilities, with further investigations completing and refining the design goal statement, incorporating the utility feedback.

The project would involve ultimately between four and eight utility organizations. Each utility is being asked to contribute two staff members to work at MIT, the oversight involvement of a vice president and the financial support for two MIT investigators plus associated graduate students. The project director is Professor Michael W. Golay of the MIT Nuclear Engineering Department.

In launching this project extensive discussions regarding support and program directions have been held with the U.S. Department of Energy, the Nuclear Regulatory Commission, the Office of Science and Technology, the Electric Power Research Institute, the Tennessee Valley Authority, Commonwealth Edison Co., and Duke Power Corp. Contacts have also been established for information exchange and cooperation with many of the important nuclear

## Table 1

Summary of Technical Tasks in Initial Phase
of MIT LWR Innovation Project

Overall Purpose: Significant improvement of LWR economics and safety through design goal refinement.

| Parallel Approaches | First-Year Project |
|---|---|
| Simplification | Development of reliability-oriented simplification methodology using PWR chemical and volume control system simplification as an example. |
| Introduction of new technology | Advanced system diagnosis and control system design and implementation |
| Refinement of Safety requirement and approaches | Exploitation of the design space allowed by regulatory acceptance of the "leak before break" concept in satisfying seismic safety requirements through much simpler, less expensive designs. |
| Improvements of trouble-some components | Comparison of performance experience and designs of main coolant pump seals and of safety relief valves. |
| Surveys of utility experience and priorities | 1. Lessons from LWR construction and operation<br>2. Materials problems and the state of knowledge<br>3. Important safety issues where needless conservatism could be reduced and/or safety could be improved. |

industrial organizations in Japan and Western Europe. The project members are expected to guide the evolution of the design goal collectively. Based upon the results of individual project investigations they will periodically revise the goal and the direction of future investigations in the project. The initial generation of investigations would be concerned substantially with distillation of the lessons of the experience of plants in the United States, Europe and Japan. Based upon the preponderance of current and likely future LWR plants, the initial project focus will be upon PWR innovation.

Investigators: Professors M. Golay, A. Henry, D. Lanning, R. Lester, J. Meyer, N. Rasmussen, and N. Todreas; Mr. V. Manno.

Support: Seed Support from Stone & Webster.

Related Academic Subjects:

| | |
|---|---|
| 22.021 | Nuclear Reactor Physics |
| 22.03 | Engineering Design of Nuclear Power Systems |
| 22.031 | Engineering of Nuclear Reactors |
| 22.033 | Nuclear Systems Design Project |
| 22.05 | Introduction to Engineering Economics |
| 22.070J | Materials for Nuclear Applications |
| 22.071J | Physical Metallurgy Principles for Engineers |
| 22.08 | Energy |
| 22.088 | Human Factors in Design |
| 22.211 | Nuclear Reactor Physics I |
| 22.212 | Nuclear Reactor Physics II |
| 22.213 | Nuclear Reactor Physics III |
| 22.311 | Energy Engineering Principles |
| 22.312 | Engineering of Nuclear Reactors |
| 22.313 | Advanced Engineering of Nuclear Reactors |
| 22.314J | Structural Mechanics in Nuclear Power Technology |
| 22.32 | Nuclear Power Reactors |
| 22.33 | Nuclear Engineering Design |
| 22.341 | Nuclear Energy Economics and Policy Analysis |
| 22.35 | Nuclear Fuel Management |
| 22.36J | Two-Phase Flow and Boiling Heat Transfer |
| 22.38 | Reliability Analysis Methods |
| 22.39 | Nuclear Reactor Operations and Safety |
| 22.40J | Advanced Reliability Analysis and Risk Assessment |
| 22.42 | Numerical Methods in Engineering Analysis |
| 22.43 | Advanced Methods in Engineering Analysis |
| 22.85J | Case Studies in Energy, Technology, Economics, and Management |
| 22.88J | Cases and Projects in Engineering Management |

Recent References:

R.K. Lester, et al., "Nuclear Power Plant Innovation for the 1990s: A Preliminary Assessment," Department of Nuclear Engineering, MIT, (September 1983).

M.W. Golay, "Refinement of Light Water Reactor Design Goals: A Plan for Action," Department of Nuclear Engineering, MIT, (October 1983).

M.W. Golay, "An Agenda for Improving Present-Day Reactors," Technology Review, pp. 49-51, (February 1984).

V.P. Manno, "Station Blackout: An Opportunity for Formulating Less Prescriptive Nuclear Safety Regulation," Nuclear Engineering Department, MIT, MITNE-261, (May 1984).

J.M. Sanchez, "Elimination of Soluble Poison Systems for PWR Simplification," B.S. Thesis, Department of Nuclear Engineering, MIT, July 1984.

V.P. Manno and M.W. Golay, "Nuclear Power Plant Design Innovation Through Simplification," Nuclear Engineering and Design, submitted (August 1984).

### 3.12.2 Modular High Temperature Gas Reactor (MHTGR) Project

In response to the conclusions reached in Nuclear Power Plant Innovation in the 1990s: A Preliminary Assessment, (September 1983), we have initiated a comprehensive study of the MHTGR concept. Our initial intent is to help determine whether the MHTGR is suitable for commercial deployment in the decade of the '90s and, if so, how best to achieve this goal. Our longer range plan is to contribute to developing the ultimate potential of the MHTGR concept.

Because we cannot be equally active across the entire spectrum of issues involved in MHTGR research, we are concentrating initial efforts on safety, investment, and licensing issues. Our current projects involve issues of source-term/core-design interaction, applicability of safety goals, incentives for fuel quality improvement, and determination of design goals. We plan later to consider such questions as operational optimization and high temperature designs for process heat and/or direct cycle gas turbines. Current projects include:

a) Reactor Core Design, development and use of simple models to determine characteristics of a range of possible modular gas cooled reactors. The prime focus will be the interaction of core design and fuel characteristics in determining the source term in heat-up events. We will attempt to develop useful working definitions for "fuel quality" and determine the incentives for fuel quality improvements.

b) Economies of Scale, significant economic benefits are potentially available if advantage is taken of serial offsite fabrication, simplified plant construction, improved licensing via standardized modules, and possibly a reduced safety envelope. A dominant issue to be resolved is whether reduced specific plant costs available via serial production techniques offset the economy of scale dependence traditionally accepted by the nuclear electric industry.

c) Source Term Effects, the inherent safety features of some MHTGRs suggest substantial savings in balance-of-plant design may be made possible by rationalized licensing requirements and reduced security demands. Although new regulations may reasonably be advocated when the MHTGR is better developed and tested, reliance on new regulations at this time seems premature. We will study the application of existing regulations to the MHTGR with particular attention given to issues of confinement. We will determine which existing requirements are limiting and determine whether these requirements are compatible with economic MHTGR deployment.

d) Moisture Monitor Studies, recent developments in laboratory instrumentation suggest the possibility of substantial improvements in sensitivity, reliability, and operational ease of primary helium and moisture monitors in MHTGRs. We are evaluating physical phenomena capable of being used for the basis of moisture monitors. This is a short term study, but the area has great potential for university scale experiments, and we will try to develop this effort.

Investigators: Professors D.D. Lanning, R.K. Lester, and L.M. Lidsky

Support: Energy Lab Utility Program

Related Academic Subjects:

| | |
|---|---|
| 22.211 | Nuclear Reactor Physics I |
| 22.312 | Engineering of Nuclear Reactors |
| 22.32 | Nuclear Power Reactors |
| 22.33 | Nuclear Engineering Design |
| 22.341 | Nuclear Energy Economics and Policy Analysis |
| 22.35 | Nuclear Fuel Management |
| 22.39 | Nuclear Reactor Operations and Safety |

Recent References:

L.M. Lidsky, "The Reactor of the Future?" Technology Review, 52-56, (February-March 1984).

### 3.12.3 Nuclear Power Plant Innovation: Policy Analysis

Present conditions in the nuclear power industry are not conducive to the vigorous pursuit of technological innovation in the nuclear power plant field. For different reasons, the electric utility industry, the nuclear plant suppliers, and the government are all reluctant to undertake major new initiatives at this stage.

In late 1983, a research project was initiated to investigate the obstacles to nuclear power plant innovation and to analyze alternative strategies for government, utility, and supplier participation in innovation efforts. In parallel, an assessment of small, modular light water reactor and high temperature gas reactor system costs is under way. Finally, a study of the relationships between financial risks and technological preferences in utility capacity investment decisions under different conditions of uncert-tainty has been initiated.

Investigators: Professors R. Lester, M. Golay, D. Lanning, and L. Lidsky

Support: National Science Foundation.

Related Academic Subjects:

| | |
|---|---|
| 22.32 | Nuclear Power Reactors |
| 22.33 | Nuclear Engineering Design |
| 22.341 | Nuclear Energy Economics and Policy Analysis |
| 22.83 | Engineering Risk-Benefit Analysis |

Recent References:

R.K. Lester, "Japan's Lead in Nuclear Power," Wall Street Journal, November 16, 1983.

R.K. Lester, "The Need for Nuclear Innovation," Technology Review, (February-March, 1984).

### 3.13 Applied Plasma Physics

The role of controlled fusion power among possible long range solutions to the world's energy supply problem has become more obvious and the pace of research is quickening. International efforts in controlled fusion research has converged on several key experiments to be constructed during the next decade; the theoretical analyses are beginning to yield the results needed to predict reactor behavior; the engineering constraints have been determined and the extremely difficult task of designing an economical, power-producing reactor is occupying experts in many fields. The Nuclear Engineering Department is increasing its efforts in all of these areas, and in so doing has strengthened its ties with those national laboratories engaged in the controlled fusion program. MIT's fusion related program has gained stature and momentum with the recent consolidation of the MIT Plasma Fusion Center. The Nuclear Engineering Group has been well represented in the Center since its formation, and we expect our research programs to be appreciably strengthened.

The Department's Fusion Research Group is engaged in experimental research via participation in the Alcator projects, in several plasma physics and diagnostic development projects funded by the National Science Foundation, and in a new divertor simulation study as part of the Fusion Center's overall responsibility for the national divertor program. Our fundamental theoretical studies of plasma turbulence are continuing and are adding expertise in "device oriented" theoretical analysis. The Technology Group has played an important role in the National Magnet Laboratories High Field Tokamak Reactor Design and is engaged in an EPRI funded study of comparative reactor economics. The methodology of the Reactor Safety Study of fission reactor safety has been applied to questions of fusion reactor safety and some particularly important questions raised in this effort have been singled out for further research.

The program is carrying on a large Torsatron program following on demonstration that the force-reduced torsatron configuration offered substantial potential benefits as the basis for a full-scale fusion reactor. The first phase of this work culminated in "Torsatron Reactor Reference Design--T-1" described below. Several questions raised by this study area of further interest. As possibly important results of our work on helically stabilized systems is the Alcator-A Conversion Study. This project is studying the inclusion of the helical winding in the Alcator Bitte plate streeter and could lead to a major new MIT program.

3.13.1 Subjects of Instruction

The Department offers the following subjects in the area of applied plasma physics.

22.03: Engineering Design of Nuclear Power Systems, considers the principles of component and system design, and the operating characteristics of nuclear reactors for central station and marine power generation. A study is made of the application of the various engineering disciplines contributing to reactor design, to examine tradeoffs involved in the realization of system performance objectives. Examples are selected from current and projected U.S. reactor designs.

22.031: Engineering of Nuclear Reactors, engineering analysis of nuclear reactors, with emphasis on power reactors. Power plant thermodynamics, reactor heat generation and removal (single-phase as well as two-phase coolant flow and heat transfer) and structural mechanics. Engineering considerations in reactor design. Three lecture hours per week concurrently with 22.312 but separate assignments.

22.061: Controlled Fusion Power, is an undergraduate offering of graduate course 22.610. Both courses meet together for three lecture hours per week, but have different assignments.

22.062: Thermonuclear Reactor Design, is an undergraduate offering of graduate course 22.621. Both courses meet together, but assignments differ.

22.610: Controlled Fusion Power, introduces controlled fusion concepts: 1) fundamental plasma physics required to understand fusion reactors; 2) basic methods of producing and confining fusion plasmas; 3) description and critique of proposed fusion reactor schemes. Includes appropriate reviews of electromagnetic theory and other necessary skills to prepare students for more specialized fusion studies in the Department of Nuclear Engineering.

22.611J: Introduction to Plasma Physics I, is an introduction to plasma phenomena relevant to energy generation by controlled thermonuclear fusion and to astrophysics. Coulomb collisions and transport processes. Motion of charged particules in magnetic fields; plasma confinement schemes. MHD models; simple equilibrium and stability analysis. Two-fluid hydrodynamic plasma models; Wave propagation in a magnetic field. Introduces kinetic theory; Ulasov plasma model; electron plasma waves and Landau damping; ion-acoustic waves; streaming instabilities.

22.612J: Introduction to Plasma Physics II, deals with linear waves and instabilities in magnetized plasma; solutions of Vlasov-Maxwell equations in homogeneous and inhomogeneous plasmas; conservation principles for energy and momentum; negative energy wave; absolute and convective instabilities. Quasi-linear theory and conservation principles; evolution of unstable particle distribution functions. Collisional transport theory; Fokker-Planck equations; particle diffusion, thermal conductivity, and viscosity in magnetized plasma.

22.615J: MHD Theory of Magnetic Fusion Systems I, deals with the theory and applications of ideal MHD theory to magnetic fusion systems. The subject includes a derivation of the MHD equations, illustrating the physics described by the model and the range of validity. A basic description of equilibrium and stability of current magnetic fusion systems such as tokamak, stellarator/torsatron, and reverse field pinch is given.

22.616: MHD Theory of Magnetic Fusion Systems II, is a continuation of 22.615J. Theory and application of nonideal MHD theory including: resistive instabilities, tearing modes, resistive interchanges, nonlinear saturation, with applications to sawtooth oscillations and major disruption in a tokamak; finite Lamor radius stabilization of ideal MHD modes and rotationally driven instabilities; the Kruskal-Oberman Energy Principle for the Guiding Center MHD plasma and its application to simple axisymmetric mirrors, non-axisymmetric mirrors and the tandem mirrors.

22.622: Special Topics in Thermonuclear Reactor Design, is a class project with the goal of integrating the wide range of plasma physics, technology, and economic constraints involved in the design of large scale fusion research devices such as beam driving neutron sources, torsatron scaling experiments, copper coil ignition experiments. Usually follows the entire design process from project definition to formal presentation.

22.63: Engineering Principles for Fusion Reactors, is an introductory course in engineering principles and practices of systems relevant to controlled fusion. Topics covered include mechanism and technique for plasma production, vacuum engineering based on considerations of free molecular flow, surface physics and standard design practices, magnetic field generation by normal, cryogenic and superconduction coils: electrical, heat transfer and structural requirements, high voltage engineering and practices, methods of plasma heating: ion, electron and neutral beam production, microwave and laser systems, applications to fusion systems.

22.64J: Plasma Kinetic Theory, content varies from year to year. Typical subjects: the linearized Vlasov equation, Fokker-Planck and diffusion approximations for the average distribution function, autocorrelation functions, resonant and nonresonant diffusion, free energy, energy and momentum conservation, resonant wave coupling, non-linear Landau damping, strong turbulence theories. Selected applications to enhance diffusion, stochastic acceleration, turbulent resistivity, shock waves, radio emission.

22.65J: Advanced Topics in Plasma Kinetic Theory, varying content including topics of current interest. Typical subjects: theories of collective phenomena such as linear instability and non-linear saturation mechanisms in plasma, particularly in regimes described by the Vlasov-Maxwell equations. Effects of wave-particle resonance; trapping and scattering of particles by waves. Linear theory in instabilities in inhomogeneous plasma. Reflection and eigenmode problems in bounded systems. Diffusion phenomena and anomalous resistivity associated with wave-particle interaction. Discussion of experiments.

22.66: Plasma Transport Phenomena, transport theory analyzes the processes by which particle energy, momentum, and mass diffuse across the magnetic field. Develops the collisional classical and neoclassical transport theory of tokamaks (and stellarators) including the theory of MHD equilibrium, particle orbits and Fokker Planck operators, for the hydrogenic and impurity ions, as well as injected and alpha particles. Emphasizes connection to experimental confinement and achievement of high beta.

22.67: Principles of Plasma Diagnostics, is an introduction to the physical processes used to measure the properties of plasmas, especially fusion plasmas. Measurements of magnetic and electric fields, particle flux, refractive index, emission and scattering of electromagnetic waves and heavy particles; their use to deduce plasma parameters such as particle density, pressure temperature, velocity, etc. and hence the plasma confinement properties. Discussion of practical examples and assessments of the accuracy and reliability of different techniques.

22.69: Plasma Laboratory, introduction to the advanced experimental techniques needed for research in plasma physics and useful in experimental atomic and nuclear physics. Laboratory work on vacuum systems, plasma generation and diagnostics, physics of ionized gases, ion sources and beam optics, cryogenics, magnetic field generation and other topics of current interest. Meets with 22.069, but assignments differ.

Most undergraduate students interested in the area of applied plasma physics take 22.03, 22.031, and 22.062. For graduate students specializing in this field, recommended subjects would be 22.610, 22.611J, 22.612J, 22.615J, 22.64J and 22.69.

### 3.13.2 Fusion Reactor Environmental and Safety Studies

The overall objectives of these studies are the development of a methodology suitable for safety and environmental analysis of proposed fusion reactor power plants and the development of criteria to guide designs in order to ensure admissible environmental risks.

This effort was initiated in October 1976. Several sub-tasks have been addressed. The major achievements of the last two years can be summarized as follows:

1) <u>The Materials Impact on Reactor Safety</u>

Seven potential safety concerns for D-T fusion reactors were examined and the influence of blanket material choice determined. This influence was quantified in terms of Relative Consequence Indices (RCI) according to prescribed consequence criteria. The safety concerns include:

a) continued plasma heating after a cooling disturbance

b) decay heat removal after a cooling disburbance

c) plasma disruption effects

d) transients due to rapid chemical combustion or leakage of pressurized fluids,

e) rapid structural oxidation and volatilization

f) corrosion, and

g) public health consequences of unit volume amounts of released radioactivity

Selected combinations of structural material (316 SS, HT-9, V-alloy, or TZM), primary coolant (pressurized water, helium, lithium, or flibe), and tritium breeder (LiA10 , lithium, or Li Pb ) were examined. The analyses and indices were structured to focus on the specific material properties that influence the results, which allows for comparison of materials not included in the present study.

The safety concerns that were found to be relatively insensitive (differing by less than an order of magnitude) to material choice are: the rate of temperature increase from continued plasma heating following a loss of coolant and electromagnetic effects of plasma disruptions. The range of the RCI's was about an order of magnitude for problems concerning afterheat removal, corrosion, and the thermal effects of disruptions. The severity of the following problems were found to range over several orders of magnitude according to material choice: potential public health effects from radioactivity release, rapid structural oxidation, blanket chemical combustion and coolant pressurization.

This effort demonstrated that it is possible to quantify the relative merits of various materials from a safety perspective. However, due to conflicting preferences from individual safety problems, the overall material choice is tempered by the ability of the design to render certain accidents improbable. When combustion, rapid structural oxidation, and the thermal effects of plasma disruptions are assumed solvable by identified design approaches, the Relative Consequence Indices relating to the most important safety problems illustrate the advantages of vanadium, liquid metals, and flibe.

2) Lithium Fire Modeling

LITFIRE is a computer code that simulates the combustion of lithium in various containment schemes. The accuracy of LITFIRE in predicting thermal and pressure responses of containment atmosphere and structures has been tested against small scale (100 kg. Li) spills performed at the Hanford Engineering Development Laboratory. The agreement between experiment and LITFIRE prediction was within 10%.

Modifications to the code have been made to increase its utility in modeling fires in fusion reactor containments. The ability to monitor lithium-lead alloy reactions in air has been incorporated into LITFIRE. Also, the geometry has been made more flexible and the available options made compatible with one another. Preliminary comparisons indicate that lithium-lead alloys are much less reactive than pure lithium and generate maximum cell gas temperatures that are at least a factor of two lower than those resulting from pure lithium fires, for the same volume of liquid metal spilled.

Application of LITFIRE to fires in a prototypical fusion reactor was made. The predictions of LITFIRE indicate that fires within the torus of a tokamak fusion reactor would be much less severe than fires resulting from spills directly onto the containment building floor. However, the primary wall and surrounding structures would become hotter in spills inside the torus because they are directly exposed to radiative heating by the fire.

3) Structural Response to Plasma Disruptions

A rapid method was developed for computing the 1-D structural response to eddy current loading in a torus. Since all of the currents are directed toroidally, the structure and the driving currents are modeled as a set of circular loops which couple to one another through mutual inductances. The resulting circuit equations are solved in time, depending upon the characteristics of the driving current.

Small scale experiments have been conducted to measure the strain due to electromagnetic effects of simulated plasma disruptions. The results indicate that the effects induced strains are about an order of magnitude higher around structural discontinuities.

Investigators: Professors M.S. Kazimi, L.M. Lidsky; Messrs. S. Piet, M. Tillack, V. Gilberti, E. Yachimiak, Ms. D. Hanchar.

Support: U.S. Department of Energy and EG&G, Idaho.

Related Academic Subjects:

22.38 Reliability Analysis Methods
22.621 Thermonuclear Reactor Design

Recent Publications:

A. General Safety and Risk Assessment

S.J. Piet, M.S. Kazimi and L.M. Lidsky, "Potential Consequences of Tokamak Fusion Reactor Accidents: The Materials Impact," PFC/RR-82-19, Plasma Fusion Center, MIT, (June 1982).

S.J. Piet, V.J. Gilberti, "FUSECRAC: Modifications of CRAC for Fusion Application," Department of Nuclear Engineering and Plasma Fusion Center, PFC/RR-82-20, MIT, (June 1982).

M.S. Kazimi, "Safety and Risk Targets for Fusion Energy," Societe Francaise de Radioprotection 10th Annual Congres, Avignon, France, October 18-22, 1982.

M.S. Kazimi, "Safety Methodology and Risk Targets," in Proc. of 1981 IAEA Workshop on Fusion Safety, IAEA-TECDOC-277, 1983.

M.S. Kazimi, "Risk Considerations for Fusion Energy," Nuclear Technology/Fusion, Vol. 4, No. 2, Part 2, pp. 52-532, (September 1983).

S.J. Piet, M.S. Kazimi and L.M. Lidsky, "Relative Public Health Effects from Accidental Release of Fusion Structural Radioactivity," Nuclear Technology/Fusion, Vol. 4, No. 2, Part 2, pp. 533-538, (September 1983).

S.J. Piet, M.S. Kazimi and L.M. Lidsky, "Modeling of Fusion Activation Produce Release and Reactor Damage from Rapid Structural Oxidation," Nuclear Technology/Fusion, Vol. 4, No. 2, Part 3, pp. 1115-1120, (September 1983).

B. Lithium Reactions

M.S. Tillack and M.S. Kazimi, "Modeling of Lithium Fires," Nuclear Technology/Fusion, Vol. 2, No. 2, pp. 233-245, (April 1982).

V.J. Gilberti and M. S. Kazimi, "Modeling of Lithium and Lithium-Lead Reactions in Air Using LITFIRE," PFC/RR-82-08, Plasma Fusion Center, MIT, (January 1983).

E. Yachimiak, V. Gilberti and M.S. Tillack, "LITFIRE User's Guide," Department of Nuclear Engineering and Plasma Fusion Center, PFC/RR-82-11, (June 1983).

C. Tritium

D.R. Hanchar and M.S. Kazimi, "Tritium Permeation Modeling of a Conceptual Fusion Reactor Design," PFC/RR-82-27, Plasma Fusion Center, MIT, (July 1981).

D.R. Hanchar and M.S. Kazimi, "Transient Tritium Transport in a Solid Breeder Blanket," Nuclear Technology/Fusion, Vol. 4, No. 2, Part 2, pp. 395-400, (September 1983).

D. Electromagnetic Consideration

M.S. Tillack, "A Study of Structural Responses to Plasma Disruptions in Toroidal Shells," Department of Nuclear Engineering and Plasma Fusion Center, PFC/RR-83-16, MIT, (June 1983).

### 3.13.3 Fusion Reactor First Wall Design

Many fusion reactor designs use arrays of cooling tubes or variations of this proven heat transfer technology for the first wall. However, no complete solution exists for handling the inevitable leaks that will develop in this complex and critical tube array structure. Here we consider an approach that designs for leaks--that is, it permits a reasonable level of leak-tolerance in the design. In particular, each tube is designed with sufficient operating margin to handle the extra load if adjacent tubes are turned off because of leaks. Earlier work on the development of a design limit approach to optimizing fusion blankets was applied to examine this redundancy requirement. In this approach, desired parameters and constraints, including this redundancy requirement, are used to define the allowed range or design window for the remaining free variables.

The results indicate that leak-tolerance is possible with a three-header first wall design and with the first wall thermal load below about 0.2 MW/m**2. This implies neutron wall loads of 1 MW/m**2, appreciably less than the 4 MW/m**2 of such recent tokamak designs as STARFIRE, but compatible with near-term machines such as FED or possibly on commercial mirror reactors. In any event, the principles outlined may be compatible with higher wall loadings by adjusting other parameters such as tube length.

Investigators: Professors N.E. Todreas, and B. Mikic (Department of Mechanical Engineering); P. Gierszewski.

Support: U.S. Department of Energy

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors
22.621 Thermonuclear Reactor Design

Recent Publications:

B. Mikic, N.E. Todreas, and P. Gierszewski, "Design Limit Analysis of Redundant Tube Array First Walls," PFC/RR-82-32, (December 1982).

### 3.13.4 Theory of Magnetically Confined Toroidal Plasma

One purpose of this activity is to determine the important MHD equilibrium and stability limits (both ideal and resistive) of magnetic confinement systems, in particular tokamaks, torsatrons, EBT and tandem mirror. Specifically, one needs to calculate  limits and current limits for MHD stability to determine whether or not extrapolation of reactor size and economics are favorable. Equally important, one must learn how the critical plasma parameters (i.e., , q, helical current, etc.) scale with basic geometries and technological constraints (i.e., aspect ratios, ring current, beam energy, etc.) in order to optimize the design of future experiments and possible reactors. The approach to be used consists of solving the ideal and resistive MHD equilibrium and stability equations primarily by analytic, asymptotic techniques. The calculations are carried out for special simple profiles as well as for general diffuse profiles. Small to moderate computations are required for evaluation purposes.

Another purpose of this activity is to develop a self-consistent microturbulence theory for magnetic confinement systems, primarily toroidal (tokamak and stellarator) systems. Such turbulence often gives rise to anomolous transport which can far exceed the clasical collisional transport. Successful reactor designs will depend largely on our ability to predict and/or scale these anomalous transport processes theoretically. Although our present understanding of the anomalous loss processes in tokamaks is minimal (the <u>mechanism</u> of anomalous losses is not known), several recent developments appear to be converging on the solution to this problem. They are: (a) appreciation of the importance of very small magnetic perturbations in electron transport, (b) experimental evidence (through understanding the soft x-ray anomaly) from Alcator and T10 that magnetic fluctuations are the <u>mechanism</u> of anomalous heat loss, and (c) development of a self-consistent <u>turbulence</u> theory for the magnetic fluctuations associated with the universal drift instability in a screw pinch.

The predicted transport coefficients (anomalous electron thermal conductivity) have many similarities with experimental observations including absolute magnitude, and scaling with density, temperature, magnetic field and ion mass. This activity is the subject of continuing development, with work in progress on the determination of the saturated spectrum, comparison with experimental data, and inclusion of effects associated with toroidal geometry and the ambipolar field, as well as the determination of the complete Onsager matrix of anomalous transport coefficients.

<u>Investigators</u>: Professors J.P. Friedberg, K. Molvig, Dr. A.B. Rechester, M. Gerver; Messrs. K. Swartz, K. Hizanidis, D. Thayer, E. Esarey, W.H. Choe, P. Hakkarainen, G. Hilfer.

<u>Support</u>: U.S. Department of Energy.

<u>Related Academic Subjects</u>:

22.611J Introduction to Plasma Physics I
22.615J MHD Theory of Magnetic Fusion Systems I
22.64J Plasma Kinetic Theory
22.65J Advanced Topics in Plasma Kinetic Theory

Recent References:

None to date.

### 3.13.5 Theory of Nonlinear and Turbulent Fluctuations in Plasma

Most plasmas of laboratory or astrophysical interest contain a non-thermal spectrum of fluctuations. These fluctuations are generally non-linear and turbulent and play a major role in determining the important properties of the plasma. For example, in plasmas of thermonuclear interest, such fluctuations can transport heat and particles across the magnetic field lines at a rate greatly in excess of the collisional rate. Also, non-linear fluctuations can enhance the rate of plasma heating for a given current in the plasma. The study of these fluctuations is not only worthwhile from the point of view of practical applications, but is an important problem in many-body physics. For example, our work is closely related to problems in fluid turbulence and the dynamics of self-gravitating systems. Generally speaking, non-linear and turbulent fluctuations are the end result of linear instabilities, which have grown past the linear stage. Unfortunately, the resulting fluctuations frequently bear little resemblance to the linearly unstable waves which drive them. Our research is concerned mainly with discovering and identifying the types of nonlinear excitations that can exist and studying their properties. This research relies on two basic approaches, that of analysis and of numerical simulation. Although the numerical simulations is expensive, it provides unlimited diagnostic information concerning the microscopic properties of the system. Such information is not available in laboratory experiments. The analytic portion of the research consists of three parts: (1) deriving and solving kinetic equations which predict the time evolution of the fluctuations, (2) the extension of statistical mechanical arguments to apply to nonequilibrium situations, and (3) the deduction of exact nonlinear time independent solutions to the Vlasov equation in the hopes that such solutions might approximate turbulent fluctuations in some cases.

Investigators: Professor T.H. Dupree; Drs. J.J. Tetreault, R.H. Berman and H.M. Hamza.

Support: U.S. Department of Energy, National Science Foundation and Office of Naval Research.

### 3.13.6 Diverter/Limiter Plasma and Engineering Analysis

Long burn operation of fusion reactors requires continuous processing of the plasma to remove helium ash and impurities. Bundle diverters are a particular class of devices which perform this function by removing a bundle of flux from the main plasma between the toroidal field coils. Here the plasma strikes diverter target plates and becomes a neutral gas which can be pumped out. Alternate approaches include the poloidal diverter and the pumped limiter.

Heat transfer, surface erosion and gas pumping are difficult engineering problems in any diverter or limiter chamber due to the small heat transfer surface area but appreciable energy flux of energetic plasma particles. The diverter target analysis considered an actively-cooled solid target constrained by requirements on heat removal, surface erosion and fatigue life. Eight structural materials with high-pressure water cooled in tube or plate geometries were considered, in a general environment of 1 kW/cm2 heat flux, 1.67 x 10**22 ions/m2-s, 1.3 keV ions, and 10**5 90 second plasma burn cycles per year. In order to obtain best performance, the design was pushed to the limits of CHF and included swirl flow options.

In general, these conditions lead to a very severe environment. Operation for even one full power year is difficult with reliable operation for at most a few months operation. The best performance of the materials examined was with the molybdenum alloy TZM.

However, the general assumptions for plasma conditions may be conservative. The purpose of the second study was to treat hydrogen plasma and neutral gas transport in diverters and pump limiters in sufficient detail to answer some of the questions as to the actual conditions that will be expected in fusion reactors. This was accomplished with a steady-state, coupled 0-D model of the plasma core, scrape-off layer and diverter exhaust to determine gross modes of operation and edge conditions; (2) a 1-D kinetic transport model to investigate the case of collisionless plasma flow with self-consistent electric fields; and (3) a 3-D Monte Carlo treatment of neutral transport to correctly account for geometry and plasma effects in the formation of a neutral gas cloud and in neutral gas pumping.

The edge model was applied to comparing particle and energy flows in INTOR and ALCATOR-DCT with a single-null poloidal diverter, toroidal pumped limiter and advanced bundle diverter. All options yielded reasonable edge conditions. The poloidal diverter and pumped limiter were sensitive to uncertainties in cross-field diffusion and core particle confinement time--small variations could trigger transition from "hot" to "cold" edge. The bundle diverter naturally operated in a cold, high recycling condition because of the difficult return path for neutrals, and so is insensitive to the same variables. The high neutral density may also reduce the need for high-vacuum pumps.

The expected range of applicability of the kinetic model is to diverter plasmas with temperatures above roughly 50 eV--a condition that is plausible, yet is not adequately addressed with current collisional fluid models. The results include the characterization of a family of solutions with an electrostatic potential peak in the diverter region.

The neutral transport model utilizes a simple geometry that allows fast evaluation of complex 3-D systems. It has been applied to determining geometric effects for the 0-D edge model and to neutral transport calculations in advanced bundle diverters.

Investigators: Professors N.E. Todreas, and B. Mikic (Department of Mechanical Engineering); Dr. T.F. Yang (Plasma Fusion Center); Professor R. Morse (Univerity of Arizona); Messrs. P. Gierszewski, J. McMurray.

Support: U.S. Department of Energy.

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer
22.621 Thermonuclear Reactor Design

Recent Publications:

J. McMurray, N. Todreas, B. Mikic, and P. Gierszewski, "Investigation of Tokamak Solid Diverter Target Options," PFC/RR-81-23, MIT, (May 1981).

P. J. Gierszewski, P. McKenty, J. McCullen, and R. Morse, "Structure of Wall Plasma Near Diverter Neutralizer Plates or Limiters," Phys. Rev. Lett., 49(9), 650 (August 30, 1982).

P.J. Gierszewski, "Plasma/Neutral Gas Transport in Diverters and Limiters," Sc.D. thesis, Department of Nuclear Engineering, PFC/RR-83-28, MIT, (September 1983).

# 4. CURRICULUM

## 4.1 Degree Programs

The Department offers programs leading to the degrees of Bachelor of Science in Nuclear Engineering, Master of Science in Nuclear Engineering, Nuclear Engineer, and Doctor of Philosophy (or Doctor of Science) in Nuclear Engineering. The duration and objectives of these programs are quite different.

The objective of the bachelor's degree program in nuclear engineering is to provide the student with a thorough mastery of scientific and engineering fundamentals together with comprehensive experience in their applications to problems in the field of nuclear engineering. This is accomplished through a curriculum under which the student, after completing Institute Science and Humanities requirements, selects coordinated subjects in thermodynamics, fluid flow, heat transfer, strength of materials and computer modeling taught by several of the other engineering departments; this, in turn, is followed up by junior and senior year subjects in nuclear engineering which include a design course and an S.B. thesis project. In this manner, the student is prepared either for immediate employment at the S.B. level, in the nuclear industry, or for further graduate level training in nuclear engineering. In the latter case the student will, at the S.B. level, have already completed all of the core curriculum subjects now required of our S.M. students who enter without a nuclear engineering background.

The objective of the master's program is to provide students who have had sound undergraduate training in physics, chemistry or engineering with the equivalent of one year of graduate education in nuclear engineering. Although full knowledge of the subject matter and techniques of nuclear engineering cannot be obtained in one year, graduates of this program are given a sound base of knowledge which prepares them either for employment on nuclear projects or for more advanced graduate education. Minimum requirements for the master's degree are two semesters of full-time graduate instruction including thesis. The majority of the candidates for this degree, however, need a full calendar year to complete course work and thesis.

The objective of the nuclear engineer's program is to educate students for a creative career in the design aspects of nuclear engineering. Minimum requirements are four semesters of full-time graduate instruction, including a substantial thesis concerned with engineering analysis, engineering design or construction of a nuclear facility or device. Students in this program have sufficient time to learn advanced techniques for engineering analysis and design, and their creative abilities in these areas are developed through participation in engineering projects under faculty supervision.

The objectives of the doctoral program are to provide an advanced education in nuclear engineering and to challenge the student to become a leading and original contributor to her or his professional field. Students in this program are required to pass a general examination and then to complete a major research investigation of sufficient scope and originality to constitute a contribution of permanent value to science and technology. Although no set time is specified for completion of the doctoral program, most students require from three to five years. Students completing the doctor's program in nuclear engineering are prepared and motivated to work on the frontiers of nuclear technology.

## 4.2 Fields of Study

Although each student's program of study is arranged to suit her/his individual interests and objects, most programs fall into one of the twelve fields of study listed below.

1. Reactor Physics
2. Reactor Engineering
3. Nuclear Fuel Management
4. Applied Plasma Physics
5. Fusion Reactor Technology
6. Applied Radiation Physics
7. Radiological Science
8. Nuclear Materials Engineering
9. Reactor Safety Analysis
10. Nuclear and Alternative Energy Systems and Policy
11. Nuclear Chemical Engineering and Waste Management
12. Health Radiation Physics (SM only)

Most candidates for the master's degree specialize either in some combination of reactor physics and reactor engineering under the more general heading of fission reactor technology, or in applied plasma physics, nuclear materials engineering, or applied radiation physics.

The nuclear fuel management field includes so many different topics that students generally require more time than is available in the one-year master's program. The two-year engineer's degree program seems well suited to the needs of students wishing to become thoroughly trained to work in this field. Other fields appropriate for engineer's degree candidates are reactor engineering, applied plasma physics and nuclear materials engineering.

Fields 1-11 are appropriate for candidates for the doctor's degree. Doctoral candidates taking the General Examination required for that degree have the option of being examined in any one of these eleven fields.

## 4.3 Subjects of Instruction

Subjects of instruction currently offered by the Nuclear Engineering Department are listed below. The subjects are divided into different areas for convenience. The introductory subjects 22.89, Basic Electronics; 22.311, Energy Engineering Principles; and 22.71J, Physical Metallurgy Principles for Engineers; are intended for graduate students who did not have the material as an undergraduate but need the material for graduate work. Subjects designated "J" are taught jointly with other Departments, e.g. Aeronautics and Astronautics, Chemical Engineering, Civil Engineering, Electrical Engineering and Computer Science, Health Science and Technology, Materials Science and Engineering, Mechanical Engineering, Metallurgy, Ocean Engineering, Physics, and Political Science.

## Undergraduate Subjects

| | |
|---|---|
| 22.U.R. | Undergraduate Research Opportunities Program |
| 22.001 | Seminar in Nuclear Engineering |
| 22.002 | Management in Engineering |
| 22.003 | Defense and Arms Control Issues |
| 22.006 | Computer Models of Physical and Engineering Systems |
| 22.02 | Introduction to Applied Nuclear Physics |
| 22.021 | Nuclear Reactor Physics |
| 22.03 | Engineering Design of Nuclear Power Systems |
| 22.031 | Engineering of Nuclear Reactors |
| 22.033 | Nuclear Systems Design Project |
| 22.04 | Radiation Effects and Uses |
| 22.05 | Introduction to Engineering Economics |
| 22.061 | Controlled Fusion Power |
| 22.062 | Thermonuclear Reactor Design |
| 22.069 | Undergraduate Plasma Laboratory |
| 22.070J | Materials for Nuclear Applications |
| 22.071J | Physical Metallurgy Principles for Engineers |
| 22.08 | Energy |
| 22.084 | Inventions and Patents |
| 22.085 | Introduction to Technology and Law |
| 22.088J | Human Factors in Design |
| 22.09 | Introductory Nuclear Measurements Laboratory |
| 22.091 | Special Topics in Nuclear Engineering |
| 22.092 | Engineering Internship |

## Graduate Subjects

### Nuclear Physics

| | |
|---|---|
| 22.111 | Nuclear Physics for Engineers I |
| 22.112 | Nuclear Physics for Engineers II |

### Nuclear Reactor Physics

| | |
|---|---|
| 22.211 | Nuclear Reactor Physics I |
| 22.212 | Nuclear Reactor Physics II |
| 22.213 | Nuclear Reactor Physics III |
| 22.29 | Nuclear Measurements Laboratory |

### Nuclear Reactor Engineering

| | |
|---|---|
| 22.311 | Energy Engineering Principles |
| 22.312 | Engineering of Nuclear Reactors |

| | |
|---|---|
| 22.313 | Advanced Engineering of Nuclear Reactors |
| 22.314J | Structural Mechanics in Nuclear Power Technology |
| 22.32 | Nuclear Power Reactors |
| 22.33 | Nuclear Engineering Design |
| 22.341 | Nuclear Energy Economics and Policy Analysis |
| 22.35 | Nuclear Fuel Management |
| 22.36J | Two-Phase Flow and Boiling Heat Transfer |
| 22.37 | Environmental Impacts of Electricity |
| 22.38 | Reliability Analysis Methods |
| 22.39 | Nuclear Reactor Operations and Safety |
| 22.40J | Advanced Reliability Analysis and Risk Assessment |

Numerical and Mathematical Methods

| | |
|---|---|
| 22.41 | Numerical Methods of Radiation Transport |
| 22.42 | Numerical Methods in Engineering Analysis |
| 22.43 | Advanced Numerical Methods in Engineering Analysis |
| 22.44J | Computational Methods in Materials Science and Engineering |
| 22.571J | General Thermodynamics I |
| 22.572J | General Thermodynamics II |

Applied Radiation Physics

| | |
|---|---|
| 22.51 | Radiation Interactions and Applications |
| 22.55J | Biological and Medical Applications of Radiation and Radioisotopes |
| 22.56J | Principles of Medical Imaging |
| 22.57J | Radiation Biophysics |
| 22.58 | Health Physics II |

Plasmas and Controlled Fusion

| | |
|---|---|
| 22.610 | Controlled Fusion Power |
| 22.611J | Introduction to Plasma Physics I |
| 22.612J | Introduction to Plasma Physics II |
| 22.615J | MHD Theory of Magnetic Fusion Systems I |
| 22.616 | MHD Theory of Magnetic Fusion Systems II |
| 22.621 | Thermonuclear Reactor Design |
| 22.622 | Special Topics in Thermonuclear Reactor Design |
| 22.63 | Engineering Principles for Fusion Reactors |
| 22.64J | Plasma Kinetic Theory |
| 22.65J | Advanced Topics in Plasma Kinetic Theory |
| 22.66 | Plasma Transport Phenomena |
| 22.67 | Principles of Plasma Diagnostics |
| 22.69 | Plasma Laboratory |

Nuclear Materials

| | |
|---|---|
| 22.70J | Materials for Nuclear Applications |
| 22.71J | Physical Metallurgy Principles for Engineers |
| 22.72J | Nuclear Fuels |
| 22.73J | Radiation Effects in Crystalline Solids |

| | |
|---|---|
| 22.75J | Radiation Effects in Reactor Structural Materials |
| 22.76J | Introduction to Nuclear Chemical Engineering |
| 22.77 | Nuclear Waste Management |

General

| | |
|---|---|
| 22.81 | Energy Assessment |
| 22.82 | Engineering Risk-Benefit Analysis |
| 22.821 | Engineering Systems Analysis |
| 22.841 | Technology of Nuclear Weapons and Arms Control |
| 22.85J | Case Studies in Energy, Technology, Economics, and Management |
| 22.86 | Entrepreneurship |
| 22.87J | Current Issues in Engineering Management |
| 22.88J | Cases and Projects in Engineering Management |
| 22.89 | Basic Electronics |
| 22.901 to | Special Problems in Nuclear Engineering |
| 22.904 | Special Problems in Nuclear Engineering |
| 22.911 | Seminar in Nuclear Engineering |
| 22.912 | Seminar in Nuclear Engineering |
| 22.913 | Graduate Seminar in Energy Assessment |
| 22.914 | Graduate Seminar in Energy Assessment |
| 22.92 | Advanced Engineering Internship |
| 22.93 | Teaching Experience in Nuclear Engineering |
| 22.94J | Seminar on Technology and Development |

Subjects offered by other departments of special interest to Nuclear Engineering students include:

Civil Engineering

| | |
|---|---|
| 1.143J | Mathematical Optimization Techniques |
| 1.146 | Engineering Systems Analysis |
| 1.52 | Structural Analysis and Design |
| 1.581 | Structural Reliability |
| 1.77 | Water Quality Control |
| 1.78 | Water Quality Management |

Mechanical Engineering

| | |
|---|---|
| 2.032 | Dynamics |
| 2.06J | Mechanical Vibration |
| 2.092 | Methods of Engineering Analysis |
| 2.093 | Computer Methods in Dynamics |
| 2.14 | Control System Principles |
| 2.151 | Advanced Systems Dynamics and Control |
| 2.155 | Dynamics and Control of Thermofluid Processes and Systems |
| 2.20 | Fluid Mechanics |
| 2.25 | Advanced Fluid Mechanics |
| 2.301 | Advanced Mechanical Behavior of Materials |
| 2.41J | Thermodynamics of Power Systems |
| 2.55 | Advanced Heat Transfer |
| 2.56 | Conduction Heat Transfer |

Materials Science and Engineering

| | |
|---|---|
| 3.14 | Physical Metallurgy |
| 3.25J | Physics of Deformation and Fracture of Solids I |
| 3.26J | Physics of Deformation and Fracture of Solids II |
| 3.38 | Behavior of Metals at Elevated Temperatures |
| 3.39 | Mechanical Behavior of Materials |
| 3.54 | Corrosion - The Environmental Degradation of Materials |

Electrical Engineering and Computer Science

| | |
|---|---|
| 6.013 | Electromagnetic Fields and Energy |
| 6.271 | Introduction to Operations Research |
| 6.683 | Planning and Operation of Electric Power Systems |

Physics

| | |
|---|---|
| 8.312 | Electromagnetic Theory |
| 8.321 | Quantum Theory I |
| 8.322 | Quantum Theory II |
| 8.511J | Theory of Solids I |
| 8.512J | Theory of Solids II |
| 8.641 | Physics of High Temperature Plasmas I |
| 8.642 | Physics of High Temperature Plasmas II |

Chemical Engineering

| | |
|---|---|
| 10.38 | Analysis and Simulation of Chemical Processing Systems |
| 10.39 | Energy Technology |
| 10.50 | Heat and Mass Transfer |
| 10.52 | Mechanics of Fluids |
| 10.70 | Principles of Combustion |
| 10.73 | Seminar in Fuel Conversion and Utilization |
| 10.86 | School of Chemical Engineering Practice--Bethlehem Station |
| 10.87 | School of Chemical Engineering Practice--Bethlehem Station |
| 10.88 | School of Chemical Engineering Practice--Brookhaven Station |

Ocean Engineering

| | |
|---|---|
| 13.21 | Ship Power and Propulsion |
| 13.26J | Thermal Power Systems |

Economics

| | |
|---|---|
| 14.281 | The Energy Industries |

Management

| | |
|---|---|
| 15.065 | Decision Analysis |
| 15.081J | Introduction to Mathematical Programming |
| 15.084J | Nonlinear Programming and Discrete-Time Optimal Control |

Aeronautics and Astronautics

16.551 Plasma Dynamics and Magneto Hydrodynamics

Mathematics

18.085 Methods of Applied Mathematics for Engineers
18.175 Theory of Probability

## 4.4 Independent Activities Period

The January Independent Activities Period continued to be very popular over the past few years. Professor Rasmussen presented a session on "Engineering WAGS (Wise Astute Guesses)," designed to challenge engineering minds by teaching how to use rough approximations to get answers quickly. Environmental and safety concerns in fusion reactor design were discussed in the "Fusion Safety Seminar," which was offered by Professor Mujid Kazimi. A workshop on "Magnetic and Irradiation Effects on Materials Stability," was sponsored by Professor I-Wei Chen. In the session entitled, "Measuring the Motion of Bacteria with Lasers," Michael Kotlarchyk introduced participants to the use of laser-light scattering to characterize the motions of bacteria. Professor Sow-Hsin Chen presented an activity on "Small Angle Neutron Scattering: Applications in Colloidal Suspension." In the area of applied radiation physics, Professor Sidney Yip offered the following topics: "Atomistic Simulation of Materials Properties," and "Computer Simulations in Condensed Matter Science: Molecular Dynamics and Monte Carlo."

Future trends in nuclear science and engineering were discussed by a panel of experts at the session entitled, "Professional Challenges and Personal Opportunities in Matters Nuclear," organized by Professors Ron Ballinger and Michael Driscoll. Professor David Lanning presented the opportunity to operate a power reactor at the session, "Could You Operate a Nuclear Power Reactor?" "Hardware That Caused a Reactor System Problem," was discussed and was available for inspection at a review session sponsored by Professor David Lanning and Neil Todreas.

An informal discussion entitled, "Life at MIT as a Foreign Student," was sponsored by Professor Otto Harling to aid present and incoming foreign students adjust to life at MIT. Professor Andrei Schor presented a seminar series on the "Current Trends in Computers and Computer Applications."

## 4.5 Undergraduate Research Opportunities Program

The Undergraduate Research Opportunities Program is a special program to provide undergraduate students with research experience in the various laboratories and departments throughout MIT. Professor D.D. Lanning is the Nuclear Engineering Department Coordinator.

The program has provided an excellent vehicle for undergraduates to learn about the research activities in the Department. During the period from September 1981 to June 1984, 54 undergraduates were engaged in projects within the Department.

## 4.6 Changes in Nuclear Engineering Subjects

### A. New Subjects

Since the fall of 1981, 11 new subjects have been added to the curriculum. These subjects are described below.

22.05: Introduction to Engineering Economics, introduces methods used by engineers for the economic analyses of alternatives. Topics covered include time-value-of-money mechanics; present worth and rate-of-return methodology; dealing with depreciation and taxes, inflation, and escalation; levelized cost; replacement and retirement problems. Also, component cost modeling, economy-of-scale and learning-curve effects, cost-risk-benefit analysis, insurance, and other probabilistic applications are presented.

22.061: Controlled Fusion Power, introduces controlled fusion concepts: 1) fundamental plasma physics required to understand fusion reactors; 2) basic methods of producing and confining fusion plasmas; 3) description and critique of proposed fusion reactor schemes. Includes appropriate reviews of electromagnetic theory and other necessary skills to prepare students for more specialized fusion studies in the Department of Nuclear Engineering. Meets three lecture hours a week with 22.610 but with different assignments and quizzes.

22.062: Thermonuclear Reactor Design, covers the following topics: Systems analysis and design of controlled thermonuclear reactors, development of criteria for CTR feasibility on basis of economic and technical considerations, detailed critical review of DOE's prototype reference reactor designs, non-Maxwellian reactors, laser-induced fusion, blanket neutronics, fission-fusion symbiosis, radiation damage, environmental hazards. Meets with 22.621, but assignments differ.

22.088J: Human Factors in Design, presented jointly with the Mechanical Engineering Department, analyzes human and computer roles, interfacing and reliability in nuclear and chemical plants, air traffic control, industrial robots, office automation, and other systems. Introduces methods for measurement of and statistical inference about human behavior in such interactions. Reviews human sensory and motor performance characteristics and the derivation of human engineering design criteria for displays and controls. Readings from the human factors engineering literature. Case studies and design projects.

22.341: Nuclear Engineering Economics and Policy Analysis, presents a comprehensive assessment of the economic, environmental, political and social aspects of nuclear power generation and the nuclear fuel cycle. Quantitative applications of the principles of engineering economics; comparison of alternatives using discounted cash flow methods. Technology assessment/-policy analysis of institutional alternatives for R&D, management, and regulation; includes nuclear power plant licensing, nuclear waste management, and nuclear power and weapons proliferation.

22.443: Computation Methods in Materials Science and Engineering, deals with the principles and applications of methods for computing materials properties and behavior. Topics covered include atomistic simulation techniques of molecular statics, molecular dynamics, and Monte Carlo as applied to crystalline solids with and without defects; continuum modeling of fluid flow phenomena in materials processing; finite element methods; statistical techniques of error propagation and multivariate error analysis in experimental design. Hands-on experience using existing computer programs and programs developed during the term.

22.58: Health Physics II, uses the 5 MW MIT Research Reactor extensively to provide students with real experience in radiation measurement, management, and control. Other facilities include a cyclotron, linear accelerator, and power reactors. Reviews applicable standards for radiation exposure. Covers theory and use of , , , and n detectors and spectrometers. Covers preparation and handling of isotopes, shielding, analysis and design of radiation protection systems and procedures, in applications including nuclear power generation, medical and research uses of radiation.

22.616: MHD Theory of Magnetic Fusion Systems II, is a continuation of subject 22.615J. It covers the theory and application of nonideal MHD theory including: resistive instabilities, tearing modes, resistive interchanges, nonlinear saturation, with applications to sawtooth oscillations and major disruption in a tokamak; finite Larmor radius stabilization of ideal MHD modes and rotationally driven instabilities; finite Larmor radius effects of resistive instabilities; the Kruskal-Oberman Energy Principle for the Guiding Center MHD plasma and its application to simple axisymmetric mirrors, non-axisymmetric mirrors and the tandem mirrors.

22.841: Technology of Nuclear Weapons and Arms Control, reviews the technical issues bearing on nuclear weapons policy, the arms race, and arms control. Technical description of fission and fusion weapons. Effects of nuclear explosions: blast, thermal, fallout, electromagnetic pulse, and climatological. Nuclear weapons proliferation. Nuclear delivery systems. Ballistic missile defense and air defense systems. Measures of the strategic balance. Methods for detecting nuclear explosions. Arms control agreements: Test Ban, SALT I, SALT II and prospects for further agreements limiting nuclear weapons systems. This is an Engineering School-wide elective.

22.85J Case Studies in Energy, Technology Economics and Management, gives students with diverse backgrounds an opportunity to study the multi-dimensional (i.e., technological, economic, and environmental) nature of complex energy issues in a concrete context. Class is divided into working groups for specific case studies. Investigates one or more topics of current interest involving fossil fuel, nuclear, and renewable energy sources. This subject is offered jointly with the Department of Electrical Engineering and Computer Science.

22.94J: Seminar on Technology and Development, explores issues that interface development process and the technological transformation of less-industrial societies. Lectures and case studies are geared to graduate students interested in the experience and social contexts of engineering for development. This subject is taught by an interdisciplinary faculty drawn from Political Science, Anthropology, Engineering and Economics.

B. Subjects with Major Revisions

Since our last Activities Report, the following subjects have been revised extensively.

22.39: Nuclear Reactor Operations and Safety, covers the principles of operating nuclear reactor systems in a safe and effective manner. Emphasizes light water reactor systems with transient response studies including degraded core recognition and mitigation. Consequence analysis and risk assessment. Considers lessons from past accident experience. Reviews NRC licensing and regulations. Demonstrations: operation of the MIT Research Reactor; use of a PWR concept simulator. Optional laboratory section involves a project at the Nuclear Reactor Laboratory.

22.40J: Advanced Reliability Analysis and Risk Assessment, considers the extended application and use of reliability and probabilistic risk analysis methods. Methods for common mode failure analysis and treatment of dependencies are discussed. Bayesian statistic applied to systems reliability and safety problems. Other topics include: error/sensitivity analysis; time dependent reliability analysis, Markov models, systems availability, and systems performance; replacement and maintenance strategy development. Case studies of safety analyses in nuclear and nonnuclear areas. This course is also offered by the Department of Ocean Engineering.

22.42: Numerical Methods in Engineering Analysis, applies digital computers to the solution of engineering problems. Reviews specific mathematical techniques, such as linear algebra, interpolation, and finite difference equations. Also considers topics such as: numerical solution of ordinary differential equations; fundamentals of consistency, convergence, stability, and accuracy; numerical solution of elliptic, parabolic, and hyperbolic partial differential equations. Special topics from nuclear reactor physics, heat transfer, and fluid dynamics. Applications emphasized through assignments requiring use of computer.

22.43: Advanced Numerical Methods in Engineering Analysis, covers advanced computational methods used in analysis of nuclear reactor engineering problem studies. Emphasizes the solution of multidimensional problems and non-linear equations using modern iterative techniques. Topics include finite difference and finite elements formulations with applications to incompressible and compressible flows. Introduction to numerical turbulence modeling. Additional special topics covered depending on the interest of the class.

22.610: Controlled Fusion Power, introduces controlled fusion concepts: 1) fundamental plasma physics required to understand fusion reactors; 2) Basic methods of producing and confining fusion plasmas; 3) description and critique of proposed fusion reactor schemes. Includes appropriate reviews of electromagnetic theory and other necessary skills to prepare students for more specialized fusion studies in the Department of Nuclear Engineering. Meets three lecture hours a week with 22.061 but with different assignments and quizzes.

22.76J: Introduction to Nuclear Chemical Engineering, deals with applications of chemical engineering to the processing of materials for and from both nuclear fission and fusion reactors. Topics covered include the principles and techniques for separation of uranium, hydrogen, and other isotopes; tritium handling; solvent extraction and ion exchange as applied to nuclear materials, including processing of irradiated fuel from fission reactors and extraction and purification of uranium from its ores; chemistry of uranium, plutonium, and fission products.

C. Subjects No Longer Offered

Since our last Activities Report, the following subjects are no longer offered by the Department.

| | |
|---|---|
| 22.07 | Basic Plasma Physics |
| 22.22 | Nuclear Reactor Dynamics |
| 22.34 | Economics of Nuclear Power |
| 22.80 | National Socio-Technological Problems and Responses |
| 22.83J | The Finite Earth |
| 22.915 | Seminar in Reactor Safety |

## 4.7 Undergraduate Program

The Undergraduate Program in nuclear engineering is

- founded on engineering fundamentals;
- illustrated by applications to practical nuclear engineering examples; and
- adjusted to individual preferences for areas of study.

The program incorporates many subjects from other MIT departments which enables the program to be given in an efficient way by using already existing resources.

### 4.7.1 Description of the Undergraduate Program

Most students are expected to choose an area of study in one of three tracks:

a) Fission Track

The fission option includes design, analysis, and operations topics associated with light water reactor plants and with other fission reactor plant concepts. This education is preparation for direct career placement or for entry to graduate school.

b) Fusion Track

The fusion option is intended for students planning careers in areas of research or engineering development for fusion power reactors. This will, in most cases, require an advanced degree. Generally, more knowledge of mathematical physics and electromagnetism is needed in this area than in the other options in nuclear engineering.

c) Radiological Sciences Track

The radiological sciences option is intended for students planning careers in medicine or biomedical engineering with particular emphasis on the applications of radiation in diagnostics and therapy.

There are other combinations of subjects that make educational sense and fit all MIT and Department requirements. Student and advisor conferences are used to determine a suitable combination for each individual.

In any of these options, the curriculum contains four major components. The first is the Institute Science Requirement, which provides the student with the appropriate foundation in physics, mathematics, and chemistry. The second component is the Institute Humanities requirement which is included in all MIT bachelor's degree programs. The third component is Engineering Principles, in which a student is expected to become familiar with the foundations of engineering practice. The particular areas the student is required to study include strength of materials, fluid flow, thermodynamics, heat transfer, and computer modeling of physical systems. The fourth component of the undergraduate curriculum is a broad-based introduction to the specialities of nuclear engineering. Thus, students take subjects dealing with the phenomena of interest from the viewpoint of the pertinent physics (e.g., neutron physics or plasma physics). Much of the introduction also deals with the study of design and system integration concepts.

This program has remained small since its inception in 1975. However, it has produced a number of quality graduates who have continued to make contributions in engineering graduate schools, in medical schools and in industry/research.

4.7.2 Subjects of Instruction

The following subjects of instruction are offered:

22.001: Seminar in Nuclear Engineering, surveys the technology and applications of nuclear power. This includes an introductory discussion of the basic phenomena of fission and fusion power and related aspects of reactor design, a discussion, by guest lecturers from the appropriate discipline, of the many applications of reactors as research tools in biology, earth sciences, medicine and physics. A demonstration of the MIT Reactor as a research tool is given.

22.002: Management in Engineering, is an introduction to the concept of management of the engineering function, as found in a variety of industrial and non-industrial settings. The subject's aim is to help students acquire:

1) recognition of the role of engineering and its relationship to other functions in getting a job done, 2) familiarity with some of the managerial tools and concepts employed in engineering organizations, 3) practice in dealing with both short- and long-term managerial problems in a range of real life circumstances, and 4) incentive to develop a career strategy relevant to engineering training. This subject is a School-wide Elective.

22.003: Defense and Arms Control Issues, reviews and analyzes nuclear and non-nuclear arms and efforts at arms control since World War II. Focus is on the interaction of technological factors, changing strategic concepts, intelligence estimates, and political judgments in the decision-making process. Topics include nuclear proliferation, Strategic Arms Limitation Talks, Mutual and Balanced Force Reductions, new military technology, and current trends in U.S. and Soviet weapons programs.

22.006: Computer Models of Physical and Engineering Systems, reduction of physical and engineering systems to simplified physical and methematical models; representation using networks; graphs and finite element methods. Process simulations using random variables (Monte Carlo techniques) and Linear and Dynamic Programming. Manipulation of the resulting models using algorithms on digital computers. Examples drawn from fields primarily of interest to scientists and engineers, with some attention to styles of problem solving. Extensive "hands-on" computing experience. (Working knowledge of FORTRAN expected. This subject is an Engineering School-wide Elective).

22.02: Introduction to Applied Nuclear Physics, is an introduction to nuclear physics and neutron physics, with emphasis on those aspects of the subject which are applied in nuclear engineering. Topics include elementary results of quantum theory and special relativity, detection of atomic and nuclear particles, properties of atomic nuclei (isotopes and isotopic masses, nuclear reactions, natural and artificially induced radioactivity, cross sections for nuclear reactions, alpha-, beta-, and gamma-decay), nuclear models, (shell-model, liquid-drop model), nuclear fission (properties of fission and their relation to the feasibility of nuclear power and its problems), slowing-down and diffusion of neutrons, neutron-induced chain reactions, thermonuclear reactions and the possibility of energy from nuclear fusion, and an introduction to radiation dosimetry.

22.021: Nuclear Reactor Physics, is an introduction to fission reactor physics covering reactions induced by neutrons, nuclear fission, slowing down of neutrons in infinite media, diffusion theory, the few-group approximation and point kinetics. Emphasis placed on the nuclear physics bases of reactor design and their relation to reactor engineering problems. Three lecture hours per week meeting concurrently with 22.211, plus a separate recitation; assignments and quizzes are different from those in 22.211.

22.03: Engineering Design of Nuclear Power Systems, considers the principles of component and system design, and the operating characteristics of nuclear reactors for central station and marine power generation. A study is made of the application of the various engineering disciplines contributing to reactor design, to examine tradeoffs involved in the realization of system performance objectives. Examples are selected from current and projected U.S. reactor designs.

22.031: Engineering of Nuclear Reactors, engineering analysis of nuclear reactors, with emphasis on power reactors. Power plant thermodynamics, reactor heat generation and removal (single-phase as well as two-phase coolant flow and heat transfer) and structural mechanics. Engineering considerations in reactor design. Three lecture hours per week concurrently phase coolant flow and heat transfer) and structural mechanics. Engineering considerations in reactor design. Three lecture hours per week concurrently with 22.312 but separate assignments.

22.033: Nuclear Systems Design Project, is a group design project involving integration of reactor physics, thermal hydraulics, materials, safety, environmental impact and economics. Students apply the knowledge acquired in specialized fields to practical considerations in design of systems of current interest. Meets concurrently with subject 22.33 but assignments differ.

22.04: Radiation Effects and Uses, studies current problems in science, technology, health, and the environment which involve radiation effects and their utilization. Topics include material properties under nuclear radiations, medical and industrial applications of radioisotopes, radiations and lasers in research, radioactive pollutants and their demographic effects. Laboratory demonstrations of methods and instruments in radiation measurements are given at the MIT Reactor. The material is presented in an essential descriptive manner, and is suitable for students interested in a general appreciation of the physical phenomena and their uses.

22.05: Introduction to Engineering Economics, introduces methods used by engineers for the economic analysis of alternatives. Topics covered include time-value-of-money mechanics; present worth and rate-of-return methodology; dealing with depreciation and taxes, inflation, and escalation; levelized cost; replacement and retirement problems. Also component cost modeling, economy-of-scale and learning-curve effects, cost-risk-benefit analysis, insurance, and other probabilistic applications are presented.

22.061: Controlled Fusion Power, introduces controlled fusion concepts: 1) fundamental plasma physics required to understand fusion reactors; 2) basic methods of producing and confining fusion plasmas; 3) description and critique of proposed fusion reactor schemes. Includes appropriate reviews of electromagnetic theory and other necessary skills to prepare students for more specialized fusion studies in the Department of Nuclear Engineering. Meets three lecture hours a week with 22.610 but with different assignments and quizzes.

22.062: Thermonuclear Reactor Design, covers the following topics: Systems analysis and design of controlled thermonuclear reactors, development of criteria for CTR feasibility on basis of economic and technical considerations, detailed critical review of DOE's prototype reference reactor designs, non-Maxwellian reactors, laser-induced fusion, blanket neutronics, fission-fusion symbiosis, radiation damage, environmental hazards. Meets with 22.621, but assignments differ.

22.069: Undergraduate Plasma Laboratory, covers basic engineering and scientific principles associated with experimental plasma physics. Investigation of vacuum pumping phenomena and gauge operation, normal and superconducting magnetic field coils, microwave interactions with plasmas, laboratory plasma production including electrical breakdown phenomena, Langmuir probe characteristics and spectroscopy are also covered.

22.070J: Materials for Nuclear Applications, is an introductory subject for students who are not specializing in nuclear materials. Topics covered include applications and selection of materials for use in nuclear applications, radiation damage, radiation effects and their effects on performance of materials in fission and fusion environments. The subject meets concurrently with 22.70J, but assignments differ.

2.071J: Physical Metallurgy Principles for Engineers, covers the following topics: crystallography and microstructure of engineering materials. Thermodynamics of alloys, structural theory of metallic phases. Rate processes in metals; solidification, solid state diffusion, oxidation, and phase transformation. Defect properties; point defects, dislocations and radiation damage. Mechanical properties; plastic deformation, work hardening, strengthening mechanisms and fracture. Recovery and recrystallization. Emphasis on structure-properties relationships, their physical interpretation and quantification. The subject meets concurrently with 22.71J, but assignments differ.

22.08: Energy, studies energy from a holistic point of view: provision, rational utilization and conservation, regulation, environmental effects, and the interconnectedness of energy with other societal sectors. Topics include resources of petroleum, natural gas, coal, nuclear and other energy forms, the technologies of providing energy from these forms, the utilization of energy in various sectors (transportation, industrial, commercial and domestic), regulatory, tax, and other institutional arrangements that affect production and use patterns, environmental costs and opportunities associated with exercising various energy strategies, both existing and proposed, and the domestic and international political, strategic and economic implications. Meets with 22.81, but some assignments differ.

22.084: Inventions and Patents, deals with the history of private and public rights in scientific discoveries and applied engineering leading to the development of worldwide patent systems. The classes of invention protectable under the patent laws of the United States, including the procedures in protecting inventions in the Patent Office and in the courts. Reviews of the past cases involving inventions and patents in (a) the chemical process industry and medical field, (b) devices in the mechanical, ocean exploration, civil, and/or aeronautical fields, (c) the electrical and electronic areas including key radio, solid-state, and computer inventions. (This subject is an Engineering School-wide Elective).

22.085: Introduction to Technology and Law, is an introduction to the basic principles and functions of law, using legal cases and materials arising from scientific and technical issues. The subject provides an understanding of the law and legal processes as they impact upon the work of engineers and scientists. Study of judicial law-making focuses on elementary civil procedure and how change in legal doctrine takes place. Examination of statutory law-making shows how federal and state power to govern grows as technology grows. Administrative law-making focuses on the regulatory agencies' role in controlling and supporting technology as well as the extent and curbs on their power. Study of law cases, using so-called "Socratic method," and of legal processes and doctrines provides insight into the lawyer's working methods. Law's task of resolving conflicts found in scientific and engineering alternatives sensitizes students to choice of values questions. This subject is an Engineering School-wide Elective.

22.088J: Human Factors in Design, presented jointly with the Mechanical Engineering Department, analyzes human and computer roles, interfacing and reliability in nuclear and chemical plants, air traffic control, industrial robots, office automation, and other systems. Introduces methods for measurement of and statistical inference about human behavior in such interactions. Reviews human sensory and motor performance characteristics and the derivation of human engineering design criteria for displays and controls. Readings from the human factors engineering literature. Case studies and design projects.

22.09: Introductory Nuclear Measurements Laboratory, deals with the basic principles of interaction of nuclear radiation with matter, statistical methods of data analysis, introduction to electronics in nuclear instrumentation, counting experiments using Geiger-Muller counter, gas-filled proportional counter, scintillation counter, and semiconductor detectors.

22.091: Special Topics in Nuclear Engineering, is a subject for undergraduates who desire to carry out a one-term project of theoretical or experimental nature in the field of nuclear engineering in close cooperation with individual staff members.

22.092: Engineering Internship, provides academic credit for two Work Assignments of XXII-A students affiliated with the Engineering Internship Program. Students register for this subject twice. Students must complete both Work Assignments in order to receive the academic credit for this subject. (Enrollment limited to students registered in Course XXII-A).

## 4.8 Engineering Internship Program

The Engineering Internship Program is available on a competitive basis in most engineering departments. It provides a strong combination of work and study experiences. The program is intended to lead to both a bachelor's and master's degree after the student's fifth year at MIT. The student has four work assignments at a single participating company (in the summers after the second, third, and fourth year and during the fall term of the fifth year). The original acceptance to the program is competitive--the student must be accepted by a participating company after a review of qualifications and a campus review.

The student is paid by the company for the work; however, it is intended that the assignments be valid learning experiences and not only a way to make money. The program provides for completing an SM thesis as part of the final work assignment.

A total of nine students--two graduate, four seniors and three juniors are now in the program. Companies which have placed students from the Nuclear Engineering Department are Brookhaven National Laboratory, Commonwealth Edison, EG&G Idaho, Stone and Webster Engineering Corporation, and Los Alamos National Laboratory.

### 4.9 Undergraduate Seminar Program

The Undergraduate Seminar Program is an Institute-wide program which offers an opportunity for students to interact with faculty members in small, informal class settings. Seminars vary tremendously both in style and topic. Some are oriented around small, informal class discussions while others may bring in speakers, go out on field trips or involve extensive laboratory projects. The following Undergraduate Seminars have been offered by the Nuclear Engineering Department since fall 1981: Controlled Fusion (L. Lidsky, K. Molvig, J. Freidberg), Electric Power Production (M. Golay), Current Developments in Nuclear Science and Engineering (M. Driscoll), Large Socio-Technological Problems (D.J. Rose), Computers & Computing in Nuclear Science & Engineering (A. Schor).

# 5. RESEARCH FACILITIES

## 5.1 M.I.T. Reactor

As of July 1976, the M.I.T. Reactor became an Institute facility. This ended a 16-year period of operation during which the Reactor was under the supervision of the Nuclear Engineering Department. During that time the MITR logged 63,083 hours at full power and 250,445 megawatt hours.

Since its shutdown in May 1974, the Reactor has been redesigned and restarted. On July 1, 1976, it was designated an Institute laboratory under the responsibility of the Vice President for Research. Professor Otto Harling was appointed Director of the Nuclear Reactor Laboratory. In this new mode of operation it is hoped that the facility will be more broadly used by the MIT research community.

The Nuclear Engineering Department will continue to be a major user of this facility. Programs in neutron scattering, fast reactor blanket studies, nuclear materials, coolant corrosion, and medical applications described earlier in this report will still depend heavily upon the reactor.

## 5.2 Inelastic Neutron Spectrometer

A powerful neutron spectrometer has been built in the MITR-II at the exit of beam port 6SH4. The construction was funded by the National Science Foundation. This spectrometer can be used for molecular spectroscopy work by measuring the coherent and incoherent double differential cross sections of thermal neutrons. The incident neutron beam can be energy-selected in the range 3 MeV - 100 MeV by a double crystal monochrometer. The scattered neutrons can be energy-analyzed at a fixed scattering angle by a multicrystal small angle analyser spectrometer or by a constant Q variable angle spectrometer. The spectrometer system has an energy resolution as high as 0.2 MeV at a moderate energy transfer.

This spectrometer is being operated by a group headed by Professor Sow-Hsin Chen. It is used to study molecular vibrational spectra in solid hydrocarbons and hydrogen-bonded solids.

## 5.3 Computing Facilities

The Department has access to many different computer systems located on the MIT campus. MULTICS, running on a Honeywell DPS 8/70 M, provides general-purpose time-sharing. An IBM 3033/N provides batch processing through CMS Batch and VS1, and time-sharing through CMS and Troll. Both batch and interactive computing are available through VAX/VMS on a VAX 11/780.

File and information transfer between these MIT computers is enabled by BITNET and CHAOSNET links. Access to computers at other universities and national laboratories is made possible through TELENET and TYMNET.

The Department has obtained a number of the more widely used reactor design and analysis codes from other nuclear computational centers and has adapted them to use with the MIT computers. These codes have been compiled in a departmental code library, where students wishing to use the codes are given assistance and instruction.

## 5.4 Nuclear Engineering Department Laboratories

The Nuclear Engineering Department laboratories are specially equipped rooms located in Buildings NW12, NW13 and 24. One room is located in the rear of the first floor of Building NW12, and the others are on the second floor of NW13. The room in NW12 is used for physics experiments associated with counter developments and activation analysis. It has been arranged to permit setting up and checking out large pieces of experimental equipment prior to putting them in the reactor.

The rooms in NW13 are equipped with laboratory-type benches and hoods, service air, water and electricity connections. These rooms are presently used for projects in medical applications and chemical engineering. In addition, there are two laser systems being used to study fluid dynamics and cooling tower drift.

General facilities also available at the laboratory include a 4096-channel analyzer, a high vacuum system, computer terminals, and a mini-computer with a CRT graphics display and hard copy capability.

The plasma teaching laboratory in Building 24 is used primarily for the joint graduate and undergraduate lab course and provides a variety of small experiments by which students can gain experience in the laboratory techniques of plasma and fusion physics.

The laboratories and the Reactor are supported by well-equipped machine and electronics shops, a low-level radioactivity counting room, a drafting room, and a reading room stocked with nuclear engineering texts, references and journals.

# 6. DEPARTMENT PERSONNEL

## 6.1 Faculty

Neil E. Todreas

Professor of Nuclear Engineering, Head of the Department;
B. Mech.E. '58, Cornell; Sc.D. '66 (nuclear engineering) MIT;
Reactor engineering; reactor thermal analysis; reactor safety; heat transfer and fluid flow.

Ronald G. Ballinger

Assistant Professor of Nuclear Engineering and Materials Science & Engineering; S.B. '75 WPI; S.M. '77 (nuclear), S.M. '78 (materials science), Sc.D. '82 (nuclear materials engineering) MIT;
Fatigue; corrosion fatigue; stress corrosion cracking behavior in nuclear systems; fuel behavior modeling.

Manson Benedict

Institute Professor Emeritus; Profesor of Nuclear Engineering;
B. Chem. '28 Cornell; S.M. '32, Ph.D. '35 (physical chemistry) MIT;
Processing of nuclear materials; isotope separation; reactor fuel cycles; nuclear power economics.

Gordon L. Brownell

Professor of Nuclear Engineering; Head, Physics Research Lab., Massachusetts General Hospital; B.S. '43 Bucknell;
Ph.D. '50 (physics) MIT;
Biomedical applications of radiation; radiation dosimetry; radioisotope applications; effects of radiation on materials; bioengineering.

I-Wei Chen

Assistant Professor of Nuclear Engineering; S.B. '72 National Tsing-Hua Univ.; M.S. '75 University of Pennsylvania; Ph.D. '79 (metallurgy) MIT;
Nuclear materials; radiation effects.

Sow-Hsin Chen

Professor of Nuclear Engineering; B.S. '56 National Taiwan University; M.S. '58 National Tsing-Hua University; M.S. '62 University of Michigan; Ph.D. '64 (physics) McMaster University;
Applied neutron physics; physics of solids and fluids; nuclear reactor physics; biophysical applications of laser light scattering.

Michael J. Driscoll

Professor of Nuclear Engineering; B.S. '55 Carnegie Tech; M.S. '62 University of Florida; Ph.D. '66 (nuclear engineering) MIT;

Fast reactor physics; reactor engineering; economics of nuclear power.

Thomas J. Dupree

Professor of Nuclear Engineering and Physics; B.S. '55, Ph.D. '60 (physics) MIT;

Mathematical physics; particle transport theory; plasma kinetic theory.

Jeffrey P. Freidberg

Professor of Nuclear Engineering; B.E.E. '61, M.S. '62, Ph.D. '64 (elec. - phys.) Polytechnic Institute of Brooklyn;

Plasma theory; MHD theory.

Michael W. Golay

Associate Professor of Nuclear Engineering; B.M.E. '64 University of Florida; Ph.D. '69 (nuclear engineering) Cornell University;

Reactor engineering; fluid mechanics; environmental and safety problems of nuclear power.

Elias P. Gyftopoulos

Ford Professor of Engineering; Dipl. in ME & EE '53 Athens; Sc.D. '58 (electrical engineering) MIT;

Reactor dynamics; control system analysis; thermionic conversion; thermodynamics; reliability analysis.

Kent F. Hansen

Professor of Nuclear Engineering; S.B. '53, Sc.D. '59 (nuclear engineering) MIT;

Reactor mathematics; neutral particle transport; computational methods; nuclear fuel management.

Otto K. Harling

Professor of Nuclear Engineering; Director, Nuclear Reactor Laboratory; B.S. '53 Illinois Institute of Technology; M.S. '55 University of Heidelberg; Ph.D. '62 (physics) Penn State University;

Neutron scattering; experimental nuclear physics; nuclear materials; plasma surface interaction.

Allan F. Henry

Professor of Nuclear Engineering; B.S. '45, M.S. '47, Ph.D. '50 (physics) Yale;
Reactor kinetics; reactor design methods.

Ian Hutchinson

Associate Professor of Nuclear Engineering; B.A. '72 Cambridge University; Ph.D. '76 (plasma physics) Australian National University;
Plasma physics; controlled fusion.

Irving Kaplan

Professor of Nuclear Engineering, Emeritus; A.B. '33, A.M. '34, Ph.D. '37 (chemistry) Columbia;
Nuclear physics; reactor analysis; reactor physics measurements; history of science and technology.

Mujid S. Kazimi

Associate Professor of Nuclear Engineering; B.S. '69 University of Alexandria, Egypt; M.S. '71, Ph.D. '73 (nuclear engineering) MIT;
Reactor engineering; fast reactor safety.

David D. Lanning

Professor of Nuclear Engineering; B.S. '51 University of Oregon; Ph.D. '63 (nuclear engineering) MIT;
Reactor operations; reactor engineering; reactor safety; reactor physics measurements.

Richard K. Lester

Associate Professor of Nuclear Engineering; B.S. '74 London; Ph.D. '79 (nuclear engineering) MIT;
Nuclear chemical engineering; radioactive waste disposal; energy policy; nuclear proliferation.

Lawrence M. Lidsky

Professor of Nuclear Engineering; B.E.P. '58 Cornell; Ph.D. '62 (nuclear engineering) MIT;
Plasma physics; fusion reactor design.

John E. Meyer

Professor of Nuclear Engineering; B.S. '53, M.S. '53, Ph.D. '55 (mechanical engineering) Carnegie Institute of Technology;
Structural mechanics; heat transfer and fluid flow.

Kim Molvig

Associate Professor of Nuclear Engineering; B.S. '70 Cornell; Ph.D. '75 (physics) University of California.
Theoretical plasma physics.

Alan C. Nelson

W.M. Keck Assistant Professor of Biomedical Engineering; Assistant Professor of Nuclear Engineering; Assistant Professor in the Whitaker College of Health Science, Technology and Management;
B.A. '72 University of So. California; M.A. '76 University of Calfornia; Ph.D. '80 (radiation biophysics and medical physics) University of California.
Radiation biophysics; biomedical applications of radiation.

Norman C. Rasmussen

McAfee Professor of Engineering; Professor of Nuclear Engineering;
A.B. '50 Gettysburg; Ph.D. '56 (physics) MIT;
Reactor safety; environmental effects of nuclear power; reliability analysis; risk analysis.

David J. Rose

Professor of Nuclear Engineering; B.A.Sc. '47 British Columbia; Ph.D. '50 (physics) MIT;
Energy and environmental policy; energy technology; controlled nuclear fusion.

Kenneth C. Russell

Professor of Nuclear Engineering and Professor of Metallurgy;
Met.E. '59 Colorado; Ph.D. '64 (nuclear engineering) Carnegie Institute of Technology.
Radiation effects to structural material; nuclear materials.

Andrei Schor

Assistant Professor of Nuclear Engineering;
Ph.D. '83 (nuclear engineering) MIT;
Numerical methods; mathematical modeling; reactor thermal-hydraulic analysis.

Dieter J. Sigmar

Adjunct Professor of Nuclear Engineering; M.S. '60, Ph.D. '65 Technical University of Vienna;
Theory of fully ionized plasmas; controlled thermonuclear fusion research; statistical mechanics of plasmas and fluids.

Sidney Yip

Professor of Nuclear Engineering; B.S. '58, M.S. '59, Ph.D. '62 (nuclear engineering) University of Michigan.
Transport theory; neutron scattering; statistical mechanics; radiation effects.

## 6.2 Complete Listing of Personnel (as of September 1984)

### Professor

E. Beckjord (Visiting)
M. Benedict (Institute Professor Emeritus)
G.L. Brownell
S.H. Chen
M.J. Driscoll
T.H. Dupree (joint w/Physics)
J.P. Freidberg
E.P. Gyftopoulos (joint w/Mech.)
K.F. Hansen
O.K. Harling
A.F. Henry
I. Kaplan (Professor Emeritus)
D.D. Lanning
L.M. Lidsky
J.E. Meyer
N.C. Rasmussen
D.J. Rose
K.C. Russell (joint w/MS&E)
N.E. Todreas (Department Head)
S. Yip

### Associate Professor

M.W. Golay
I.H. Hutchinson
M.S. Kazimi
R.K. Lester
K. Molvig

### Assistant Professor

R.G. Ballinger (joint w/MS&E)
I.W. Chen (joint w/MS&E)
V. Manno (Visiting)
A.C. Nelson (joint w/Whitaker College of HS, T&M)
A. Schor

### Adjunct Professor

D.J. Sigmar

### Senior Research Engineer

D.B. Montgomery
J.E.C. Williams

### Sponsored Research Staff

R. Morton

### Principal Research Scientist

M.M. Miller

### Administrative Officer

J.B. deVries Gwinn

### Administrative Staff

C.M. Egan
W.J. Fitzgerald

### Research Affiliate

D.C. Aldrich
R. Hobbins
J.H. Hopps, Jr.
W.E. Vesely
L. Wolf

### Support Staff

L. Arduino
L. Bedirian
S. Congleton
M. Doubleday
G. Jacobson
E. Kehoe
M. Levine
C. Lydon
E. Parmelee
D. Radcliffe
G. Rook
L. Suter

## 6.3 Complete List of Graduate Student Staff (as of Spring 1984)

### Teaching Assistants

Abraham, Jay
Burkholder, Kirby
Cooper, Susan (P.T.)*
Crotinger, James
Day, Brian
Dimitrijevic, Vesna (P.T.)
Dorrell, Deirick (P.T.)
George, Varghese (P.T.)
Hakkarainen, Simo (P.T.)
Khalil, Yehia
Lau, S.H. (P.T.)
Malbrain, Carl (P.T.)
Miller, Ron (P.T.)
Moinzadeh, John
Rhee, Bo Wook
Seong, Poong
Sheu, Eric
Tsai, C.K.
Wittmeier, Richard
Yang, Y.S. (P.T.)

### Research Assistants

Best, Susan
Branan, Gregory
Bursuc, Ionel
Butt, Glenn (supplement)
Cavoulacos, Panos
Chang, Moon Hee (supplement)
Cheng, Shih-Kuei
Choe, Won Ho
Cooper, Susan (P.T.)
Dimitrijevic, Vesna (P.T.)
Efthimiadis, Apostolos
Esarey, Eric
Farish, Thomas
Ferrara, W. R.
Foord, Mark
Free, Scott
Gamino, Ray (supplement)
George, Varghese (P.T.)
Goodrich, Phillip
Griggs, Dan
Hakkarainen, Simo (P.T.)
Hilfer, Godehard
Huang, Tsing-Tung
Hwang, Il Soon
Iannello, Victor
Ijams, William
Izenson, Michael (supplement)
Jow, Hong Nian
Kao, Lainsu (P.T.)
Kao, Shih-Ping
Kato, Kosuke
Kotlarchyk, Michael
Kozlu, Hamdi
Labombard, Brian
LeClaire, Rene
Lee, Che-Wu
Lee, Min
Liao, Lih-Yih (supplement)
Lin, Tsang-Lang (supplement)
Liu, Dilys
Machuzak, John
Malbrain, Carl (P.T.)
Maneke, Joy
Marable, William
Moghimi, Mohammadali (P.T.)
Ornedo, Renato
Pachtman, Arnold
Parlos, Alexander
Perez, Jose
Petillo, John
Psaila, Maureen (P.T.)
Rempe, Ken
Ro, Tae Sun (P.T.)
Robinson, James
Russo, Gilberto
Sands, Mark
Schutkeker, John
Sheeks, Cynthia
Sohn, Dong-Seong
Strohmayer, Jean
Taiwo, Temitope (P.T.)
Texter, Scott
Wan, Alan
Wang, Ching
Wang, Pei-Wen
Wolford, Andrew
Wong, Frank
Yachimiak, Edward
Yang, Y.S. (P.T.)
Yoon, Peter

### Instructor G

Downar, Thomas

* (Part-time)

# 7. DEPARTMENTAL STATISTICS

## Statistical Summary

| Academic Year Sept - June | September Registration | | | | Degrees Granted | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Undergraduate | Graduate | Special | Total | B.S. | S.M. | Nucl. E. | Sc.D., Ph.D. | Total | No. of Professors | No. of Subjects |
| 51 - 52 | ---------none--------- | | | | ---------------------- | | | | | 1 | none |
| 52 - 53 | none in nuclear | | | | ----------none--------- | | | | | 2 | 4 |
| 53 - 54 | - | 8 | - | 8 | - | 4 | - | - | 4 | 2 | 5 |
| 54 - 55 | - | 20 | - | 20 | - | 13 | - | - | 13 | 2 | 5 |
| 55 - 56 | - | 46 | - | 46 | - | 10 | - | - | 10 | 3 | 6 |
| 56 - 57 | - | 74 | - | 74 | - | 32 | - | - | 32 | 5 | 7 |
| 57 - 58 | - | 93 | 1 | 94 | - | 31 | - | 2 | 33 | 6 | 8 |
| 58 - 59 | - | 95 | 6 | 101 | - | 44 | - | 7 | 51 | 8 | 12 |
| 59 - 60 | - | 102 | 6 | 108 | - | 32 | - | 5 | 37 | 10 | 14 |
| 60 - 61 | - | 112 | 10 | 122 | - | 25 | 1 | 7 | 33 | 10 | 16 |
| 61 - 62 | - | 118 | 8 | 126 | - | 34 | - | 11 | 45 | 13 | 17 |
| 62 - 63 | - | 109 | 8 | 117 | - | 27 | 1 | 12 | 40 | 15 | 20 |
| 63 - 64 | - | 103 | 10 | 113 | - | 20 | 2 | 13 | 35 | 15 | 21 |
| 64 - 65 | - | 124 | 6 | 130 | - | 24 | 3 | 14 | 41 | 16 | 24 |
| 65 - 66 | - | 125 | 6 | 131 | - | 30 | 3 | 15 | 48 | 16 | 25 |
| 66 - 67 | - | 122 | 6 | 128 | - | 28 | 11 | 22 | 61 | 18 | 26 |
| 67 - 68 | - | 132 | 4 | 136 | - | 27 | 2 | 13 | 42 | 17 | 27 |
| 68 - 69 | - | 127 | 3 | 130 | - | 35 | 6 | 14 | 55 | 18 | 28 |
| 69 - 70 | - | 128 | - | 128 | - | 31 | 8 | 22 | 61 | 20 | 28 |
| 70 - 71 | - | 111 | 3 | 114 | - | 27 | 4 | 14 | 45 | 19 | 37 |
| 71 - 72 | - | 117 | 1 | 118 | - | 20 | 2 | 19 | 41 | 20 | 35 |
| 72 - 73 | - | 115 | 1 | 116 | - | 29 | 5 | 14 | 48 | 18 | 42 |
| 73 - 74 | - | 127 | 2 | 129 | - | 32 | 12 | 8 | 52 | 19 | 49 |
| 74 - 75 | - | 138 | 7 | 145 | - | 38 | 4 | 7 | 49 | 19 | 52 |
| 75 - 76 | 20 | 182 | 2 | 204 | - | 39 | 8 | 24 | 71 | 22 | 58 |
| 76 - 77 | 33 | 188 | 2 | 223 | 2 | 37 | 10 | 23 | 72 | 24 | 61 |
| 77 - 78 | 47 | 170 | 3 | 220 | 11 | 57 | 18 | 20 | 106 | 23 | 63 |
| 78 - 79 | 41 | 172 | 1 | 214 | 11 | 40 | 10 | 15 | 76 | 19 | 58 |
| 79 - 80 | 39 | 170 | 1 | 210 | 11 | 40 | 8 | 19 | 78 | 21 | 55 |
| 80 - 81 | 35 | 154 | 2 | 191 | 10 | 34 | 7 | 20 | 71 | 24 | 62 |
| 81 - 82 | 37 | 154 | 1 | 192 | 1 | 25 | 3 | 19 | 48 | 23 | 64 |
| 82 - 83 | 33 | 164 | 0 | 197 | 8 | 30 | 4 | 15 | 57 | 24 | 67 |
| 83 - 84 | 27 | 167 | 3 | 197 | 8 | 38 | 11 | 29 | 82 | 26 | 72 |
| | | | | TOTALS | 62 | 933 | 14 | 403 | 1537 | | |

Note: AY 1972 - 1983 statistics updated to agree with Bruce Report, July 1984.

# 8. STUDENTS

Some background information about the 151 full-time graduate students registered in the Department in February, 1984, is presented in Tables 8.1 and 8.2. In past years a plurality of our students have come from undergraduate programs in physics, with mechanical engineering second. We now find nuclear engineering undergraduates are the single largest discipline.

The distribution of schools from which our domestic students are drawn is very widespread. The number coming from MIT is approximately 27%. The international student population is relatively high, approximately 51%, and reflects the widespread recognition among foreign countries of their need for nuclear power. More and more we see the trend of foreign governments sending qualified students to MIT for training in nuclear engineering.

Support for students has remained stable in recent years. In 1980/81 we had 56 research assistants, while for the spring term 1984 we have 52. We have also been most fortunate in having the support of the nuclear industry and other organizations for a limited number of fellowships.

The distribution of activities of our graduates is given in Table 8.3. The breakdown among the categories of National Laboratories, Teaching, and Industry has changed very little since our last Activities Report. A larger percentage of our recent graduates are pursuing further study. Figure 8.1 summarizes the distribution of types of first employment of our graduate students through June 1984.

Table 8.1

Background of Graduate Students Registered in Nuclear Engineering Department (Spring 1984)

By Profession (151)

Applied Physics (1)
Armament (1)
Business Administration (1)
Chemical Engineering (5)
Electrical Engineering (7)
Electricity (1)
Electronics (5)
Energy Engineering (2)
Engineering (4)
Engineering Physics (5)
Management (1)
Marine Engineering (1)
Materials Science (1)
Mathematics (4)
Mechanical Engineering (11)
Mechanics (1)
Medicine (1)
Nuclear Engineering (79)
Nuclear Physics (1)
Physics (18)
Reactor Physics (1)

By College (U.S. citizens only) (74)

Boston University (1)
Colby (1)
Edinboro State (1)
Georgia Inst. of Technology (3)
Harvard (1)
John Hopkins (1)
Kansas State University (4)
MIT (20)
New Jersey Inst. of Technology (1)
Northwestern (1)
Polytechnic Inst. of NY (1)
Princeton (1)
RPI (3)
Rutgers (1)
South Dakota State (1)
Sweet Briar (1)
University of Arizona (1)
University of California (6)
University of Florida (1)
University of Illinois (1)
University of Lowell (3)
University of Michigan (3)
University of Minnesota (1)
University of Missouri (3)
University of Oklahoma (1)
University of Pittsburgh (1)
University of Tennessee (1)
University of Texas (1)
UCLA (1)
USMA (1)
USMMA (1)
Washington and Lee (1)
Webster (1)
Western Illinois (1)
Wheaton (1)
Yale (2)

Table 8.1 (continued)

<u>By Country (151)</u>

Argentina (3)
Belgium (1)
Brazil (5)
Canada (4)
Chile (6)
Egypt (2)
Finland (1)
France (1)
Germany (1)
Greece (2)
India (1)
Iran (2)
Italy (1)
Japan (2)
Korea (11)
Lebanon (1)
Nigeria (4)
Pakistan (1)
Republic of China (18)
Romania (1)
Spain (2)
Turkey (4)
United Kingdom (1)
United States of America (74)
Venezuela (1)
Yugoslavia (1)

Table 8.2

Sources of Financial Support
(as of Spring Term 1984)

Research Assistantships (52)
Teaching Assistantships (19)
Schlumberger Fellowship (1)
NIH Trainee (1)
ACS Grant (1)
Sherman Knapp Fellowship (1)
Hertz Fellowship (1)
DOE Fusion Technology Fellowship (5)
DOE Health Physics Fellowship (1)
DOE Nuclear Science & Engineering Fellowship (1)
Draper Fellow (2)
ANL Fellowship (1)
GEM Fellowship (1)
NSF Fellowship (1)
NASA Fellowship (1)
Thompson Fellowship (1)
IBM Fellowship (1)
Consumers Power Co. Health Physics Fellowship (1)
Benedict/Rockwell Fellowship (1)
McAfee Award (1)
GSO Award (7)
U.S. Army (3)
U.S. Air Force (1)
Government of Egypt (1)
Government of Nigeria (4)
Government of Canada (1)
Government of Chile (6)
Government of Korea (5)
Government of Brazil (4)
Government of Republic of China (2)
Government of Pakistan (1)
Government of Argentina (3)
Government of Japan (1)
Government of Turkey (1)
Self-supported (10)
Did not list support (7)

Table 8.3

Activities of Nuclear Engineering Department Graduate Students

(Place of first employment -- information current as of June 1984)

U.S. Industry and Research (389) (29.0%)

Aerodyne Research Inc.
Aerojet Nuclear
Air Research Mfg. Co.
Allis Chalmers (2)
American Electric Power

Amer. Science and Eng.
APDA (2)
Assoc. Planning Res.
Atomics Int. (10)
Avco (6)

Babcock & Wilcox (8)
Battelle Columbus
Battelle Northwest (9)
Bechtel (4)
Bell Telephone Lab
Bendix
Bettis (4)
Booz, Allen & Hamilton
Burns & Roe (3)

California Oil
Combustion Eng. (21)
Commonwealth Edison (14)
Computer Processing
Conn. Mutual Life Ins.
Consolidated Edison (3)
Consultant
Consumers Power
Cornell University (research)

Detroit Power Co.
Direct Energy Con. Lab.
Douglas United Nucl. (2)
Draper Lab
Duke Power & Light (2)
Dyntech R/D Co.

Ebasco (2)
Edgerton, Germ. & Grier
EDS Nuclear
EG & G (6)
EPM, Inc.

Fauske & Associates, Inc.

Georgia Power Co.
General Atomic (5)
General Dynamics, Elec. Boat (7)
General Electric (25)
Gulf General Atomic (18)

Hercules
Hewlett-Packard
Hughes (5)
Hybrid Systems
Hanford Eng. Dev. Lab.

IBM (3)
Industrial Technology Services Inc.
Inst. for Defense Analysis
Internuclear Co.
Isotopes, Inc.

Jackson & Moreland
Jet Propulsion Lab

Lane Wells
A.D. Little (4)
Lockheed
Long Island Lighting Co.

Management & Tech. Cons.
Martin-Marietta (3)
Mass. General Hospital (5)
Maxson Electric
McKinsey & Co.
MIT (research) (23)
Mobil Oil
Monsanto
MPR Associates (3)

National Nuclear Corp. (2)
National Academy of Eng.
New England Nuclear Corp.
New England Power Service Co.
New York Law Firm
North American Rockwell (2)
Northeast Utilities Service (3)

Table 8.3 (continued)

Northern Research & Eng. (3)
Nortronics
Nuclear Fuel Service (2)
Nuclear Mater. & Equipment
Nuclear Products
Nuclear Utility Services (4)
NUS Corporation (2)
NUTECH Engineers

Perkin-Elmer Co.
Philco
Pickard, Lowe & Garrick (2)
Planning Research Corp.
Princeton (research) (5)
Public Service Elec. & Gas
Purdue (research)

Radiation Tech.
Rand Corp.
RCA Research Lab
Resources for the Future

Sanders Corp.
Science Applications (6)
Scientific Data Systems
Sloan Kettering Memorial Hospital
Smithsonian Astrophys. Obs.
Southern Calif. Edison (4)
Spire Corp.
Stanford Research Institute
S.M. Stoller Assoc.
Stone & Webster (14)
Systems Sci. & Eng.
Systems Control

Texaco
Texas Instruments
Thermo Electron (2)
TWR Systems (2)

Union Carbide
United Aircraft (3)
United Eng. & Constr. (2)

United Nuclear (5)
Univ. of Calif. (research) (2)
Univ. of Maryland (research)
Univ. of Wisconsin (research) (2)

Vacuum Industries

Watkins-Johnson
Westinghouse (30)

Yale (research) (2)
Yankee Atomic (17)

National Laboratories (93) (7.0%)

Argonne (18)
Brookhaven (7)
Knolls Atomic Power (17)
Lawrence Livermore (4)
Lawrence Radiation (5)
Los Alamos (11)
Oak Ridge (17)
Sandia (9)
Savannah River (5)

Further Study (217) (16.0%)

MIT (185)
Other (32)

U.S. Government (201) (15.0%)

Atomic Energy Commission (22)
Air Force (16)
Army (81)
Army Nuc. Def. Lab.
Army Research Lab (2)
Ballistic Research Lab
CIA
Coast Guard
Dept. of Commerce
Energy Res. & Dev. Admin. (5)
Environmental Prot. Agency (2)
NASA
National Bureau of Standards (1)
Naval Research Lab
Navy (58)
Nuclear Regulatory Comm. (4)
Peace Corps
Picatinny Arsenal
Dept. of Public Health

Teaching (62) (5.0%)

American University (Wash., D.C.)
Brooklyn College (CCNY)
Calif. State (Long Beach)
Carnegie Mellon Univ.
Case Institute
Catholic Univ. of America
Cornell
El Rancho High School
Georgia Inst. of Technology

Table 8.3 (continued)

Teaching (continued)

Howard University
Iowa State
Kansas State
Lehigh
Lowell Tech (4)
Loyola University
Mass. Maritime Academy
Michigan State University
MIT (13)
Northeastern University
Northwest Nazarene
Pennsylvania State
Princeton
Purdue
Radford College
Rensselaer Polytech.
Swarthmore
Texas A & M
U.S. Military Academy
Univ. of British Columbia
Univ. of California (7)
Univ. of Florida
Univ. of So. Florida
Univ. of Illinois
Univ. of Kentucky
Univ. of Missouri (2)
Univ. of New Hampshire
Univ. of Texas
Univ. of Washington
Univ. of Wisconsin

Foreign (216) (16.0%)

Algeria (4)
Argentina (6)
Belgium (10)
Brazil (24)
Canada (13)
Chile (6)
Columbia, S.A. (2)
England (2)
France (21)
Germany (3)
Greece (6)
India (13)
Indonesia
Iran (26)
Israel (3)
Italy (5)
Japan (15)
Jordan
Korea (3)
Libya (1)
Malaysia (2)
Mexico
Nigeria
Norway
Pakistan (3)
Philippines
Poland
Republic of China (10)
Saudi Arabia
Spain (14)
Switzerland (7)
Turkey (4)
Venezuela (5)

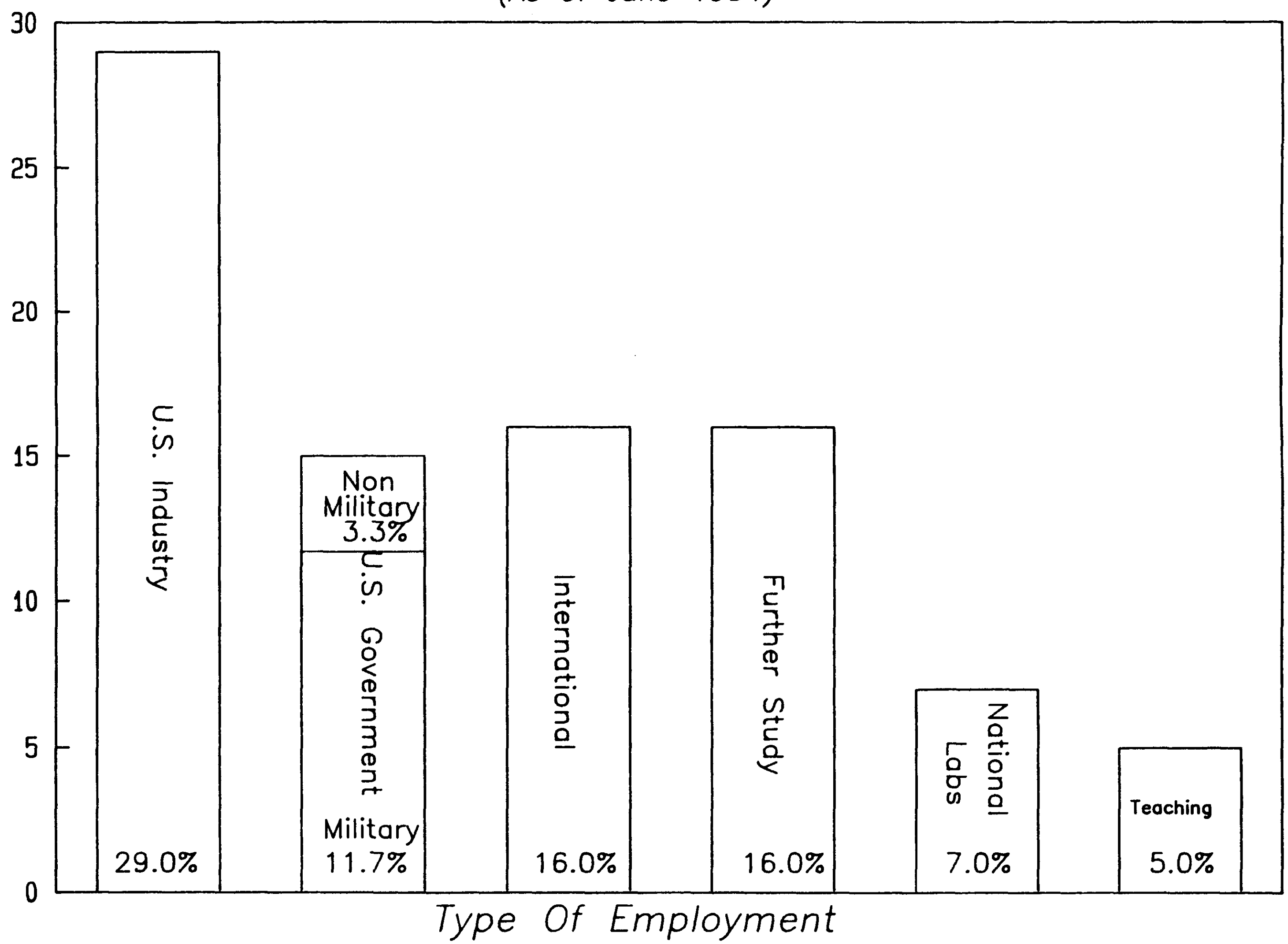
Not Reported (165) (12.0%)

TOTAL 1343*

*Records from early years are incomplete

Figure 8.1

Distribution Of First Place Of Employment
Of Nuclear Engineering Graduates*
(As of June 1984)




* Excludes 165 (12%) Students Not Reporting

# 9. LIST OF THESES

The following theses were submitted to the Department of Nuclear Engineering in September 1981:

H.A. Aljuwair, "Laser Light Scattering From Bacteria Forming Chemotactic Bands," SM Thesis.

D.P. Chou, "Continuum Theory and Molecular Dynamics Simulation of Temperature Instabilities in a Self-Heating Slab," PhD Thesis.

G.L. Dewitt, "Investigation of a Differential Heated Thermocouple Liquid Level Detector," SM Thesis.

S.G. DiPietro, "Postirradiation Characterization of Boron Coatings Subjected to Simulated Controlled Thermonuclear Reactor Conditions," SM Thesis.

B. Gulko, "Set-Theoretic Tracking: Theory and Applications," SM Thesis.

S.M. Mohammed, "Analysis of Degraded Core Cooling in Light Water Reactors," SM Thesis.

M.D. Stiefel, "Government Commercialization of Large Scale Technology: The United States Breeder Reactor Program 1964-1976," PhD Thesis.

The following theses were submitted to the Department of Nuclear Engineering in February 1982:

C.D. Antonini, "A Fault Tolerant Architecture for Nuclear Power Plant Control Systems," NE/SM Thesis.

K.J. Araj, "World Energy Strategies and the Buildup of Carbon Dioxide: An Assessment," PhD Thesis.

R.G. Ballinger, "Corrosion Fatigue of Nickel Base Alloys for Nuclear Steam Generator Applications," ScD Thesis.

R.P. Burke, "In-Plant Considerations for Optimal Offsite Response to Reactor Accidents," SM Thesis.

M. Castillo-Bonet, "Electric Utilities and Energy Conservation," NE/SM Thesis.

J.A. Combs, "Theory and Simulation of U4-Lattice Kinks in a One-Dimensional Atomic Chain," PhD Thesis.

R.C. Giovanetti, "Disposal Ship Concepts for Subseabed Disposal of Radioactive Materials," SM Thesis.

W.J. Glantschnig, "Design and Operation of a Light Scattering Device for Sizing and Velocimetry of Large Droplets," PhD. Thesis.

S.N. Kim, "LMFBR Thermal-Hydraulic Code Development and Evaluation," SM Thesis.

T.Y. Kwok, "Computer Simulation of Vacancy Motion and Diffusion Kinetics in a BCC Grain Boundary," ScD Thesis.

M.A. Malik, "Optimization of the Axial Power Shape in Pressurized Water Reactors," SM Thesis.

M.K. McQuade, "Trade-offs in Modularization of Large Fusion Systems," SM Thesis.

C.K. Nitta, "Delayed Neutron Assay to test Sorbers for Uranium-from-Seawater Applications," SM Thesis.

C.N. Wong, "Wire-Wrapped Rod Bundle Heat Transfer Analysis for Liquid Metal Fast Breeder Reactor," ScD Thesis.

O.F. Yarman, "Albedo Boundary Conditions for Hexagonal Cores," SM Thesis.

R.G. Zielinski, "Development of Models for the Two-Dimensional, Two-Fluid Code for Sodium Boiling NATOF-2D," SM/SB Thesis.

The following theses were submitted to the Department of Nuclear Engineering in June 1982:

M. Ashtari, "Biological and Physical Studies of Boron Neutron Capture Therapy," PhD Thesis.

H.A. Bazerghi, "Fuel Effectiveness in the U.S.: The Potential for Savings," PhD Thesis.

T.J. Beatty, "A Study of Simultaneous Critical Reflection and Braff Diffraction by Neutrons," SM Thesis.

B. deCelis, "Molecular Dynamics Simulation Studies in Fracture Mechanics," PhD Thesis.

S.C. Dinsmore, "A Method for Improving Accident Sequence Recognition in Nuclear Power Plant Control Rooms," SM Thesis.

A.A. Dykes, "Application of Time Dependent Unavailability Analysis to Standby Safety Systems," PhD Thesis.

C.L. Hoxie, "Application of Nodal Equivalence Theory to the Neutronic Analysis of PWRs," PhD Thesis.

K.Y. Huh, "Simulation of Sodium Boiling Experiments with THERMIT Sodium Version," SM Thesis.

J. Lingamneni, "Strategies for Increasing Oil and Gas Production in Oil Importing Developing Countries," SM Thesis.

W.T. Loh, "The Use of Burnable Poison to Improve Uranium Utilization in PWRs," PhD Thesis.

C.H. Mak, "Assessment and Comparison of Qualitative Common Cause Failure Analysis Codes," SM Thesis.

M.P. Manahan, "The Development of a Miniaturized Disk Bend Test for the Determination of Post-Irradiation Mechanical Behavior," ScD Thesis.

C.K. Park, "Reliability Analysis of the Emergency Core Cooling System of the MITR-II," NE/SM Thesis.

D.K. Parsons, "Application of Response Matrix Methods to PWR Analysis," SM Thesis.

E.I. Patterson, "Plant-Specification of Generic Human Error Data Through a Two-Stage Bayesian Approach," SM Thesis.

S.J. Piet, "Potential Consequences of Tokamak Fusion Reactor Accidents: The Materials Impact," ScD Thesis.

J.M.E. dos Santos, "Energy for Local Transportation: What We Can Learn From Cambridge, MA," SM Thesis.

S.D. Scott, "An Experimental Investigation of Magnetic Field Ripple Effects on Tokamak Plasmas," PhD Thesis.

K.A. Touqan, "Interatomic Interactions and Dynamics of Atomic and Diatomic Lattices," PhD Thesis.

C.K. Tsai, "Assessment of THERMIT Application to Initial Phase of LWR Core Uncovery," SM Thesis.

P.C. Wang, "A Study of Bacterial Motion and Chemotactic Bands by Laser Light Scattering," PhD Thesis.

The following theses were submitted to the Department of Nuclear Engineering in September 1982:

F.J. Carrion, "Molecular Dynamics Stimulation Study of Structural Stability and Melting of Two-Dimensional Crystals," SM Thesis.

B. Hagemeier, "Approximate Methods for Obtaining a One-Group Nodal Solution With Two-Group Parameters," SM Thesis.

K.E. Hizanidis, "Lagrangian Formulation of Neoclassical Transport Theory," PhD Thesis.

A. Kamal, "The Selective Use of Thorium and Heterogeneity in Uranium-Efficient Pressurized Water Reactors," ScD Thesis

N. Pisano, "Propagation of Zirconium Burning in a Spent Fuel Pool Following Loss of Water During Storage," SM Thesis.

J.M. Santos, "Thermodynamic Analysis of a Combined Cycle Coal Gasification Power Plant," NE Thesis.

D.P. Schissel, "High Energy Ion Depletion in the Charge Exchange Spectrum of Alcator C," SM Thesis.

W.H. Strohmayer, "Dynamic Modeling of Vertical U-Tube Steam Generators for Operational Safety Systems," PhD Thesis.

K. Wong, "Computer Model of a Nuclear Reactor Primary Coolant Pump," SM Thesis.

H.R. Wyle, "Effects of Thermal Neutron Irradiation Upon Erythrocyte Volume and Shape," PhD Thesis.

The following theses were submitted to the Department of Nuclear Engineering in February 1983:

F.D. Baker, "Structural Analysis of the Support Rings for a Torsatron Fusion Reactor," BS/SM Thesis.

D. Bendedouch, "Structure and Interactions of Ionic Micelles and Proteins in Solution by Small Angle Neutron Scattering," PhD Thesis.

J. Borzekowski, "Evaluation of Ion Exchange Media for the Recovery of Uranium from Seawater," SM Thesis.

P.J. Finck, "Homogenization and Dehomogenization Schemes for BWR Assemblies," PhD Thesis.

V.J. Gilberti, "Lithium Fire Modeling in Multi-Compartment Systems," BS/SM Thesis.

H. Khalil, "The Application of Nodal Methods to PWR Analysis," PhD Thesis.

G.E. Kohse, "Ion Bombardment Effects on the Fatigue Life of Stainless Steel Under Simulated Fusion First Wall Conditions," PhD Thesis.

M.A. Lopez de Bertodano, "Fast Computational Methods for Two Phase Flow Situations in Pressurized Water Reactors," NE/SM Thesis.

S.P. MacCabe, "Tapered Gyrotron Resonators," SM Thesis (Nuclear and Electrical Engineering/Computer Science).

R.F. Najafabadi, "Monte Carlo Simulation of Structural and Mechanical Properties of Crystal and Bicrystal Systems at Finite Temperatures," PhD Thesis.

H.C. No, "An Investigation of the Physical and Numerical Foundations of Two-Fluid Representation of Sodium Boiling," PhD Thesis.

V.R.L. Oliveira, "Application of the External Event Approach to Internal Event Analysis in Probabilistic Risk Analysis," SM Thesis (Nuclear and Ocean Systems Management).

S.J. Primeau, "Numerical Simulation of Void Nucleation in Metal Under Cyclic Irradiation," SM Thesis.

S.V.G. Ribeiro, "Mechanisms of Flow Induced Vibrations of Circular Cylinders in Cross Flow," SM Thesis.

J.T. Robinson, "Real-Time Computation of PWR Loss of Feedwater ATWS Transients," SM Thesis.

A.L. Schor, "A Four-Equation Two-Phase Flow Model for Sodium Boiling Simulation of LMFBR Fuel Assemblies," PhD Thesis.

R.B. Vilim, "Adaptation of On-Line Analytic Models After Fault Detection," PhD Thesis.

The following theses were submitted to the Department of Nuclear Engineering in June 1983:

D.W. Charpie, "Cost/Benefit Analysis of Stockpiling in the Nuclear Fuel Cycle," BS/SM Thesis.

F.M. Ciarletti, "An Assessment of an Integrated Energy System Using HTGR (High Temperature Gas-Cooled Reactor) and $CH_4$ as Energy Sources," SM Thesis.

W.A. Fisher, "D-D Fusion Neutron Spectra Measurements and Ion Temperature Determination at Alcator C," ScD Thesis.

S.T. Free, "Development of a Nonequilibrium, Two-Phase, Critical Flow Model," SM/SB Thesis (Nuclear and Chemical Engineering).

N.A. Ismail, "Engineering Systems Analysis of Uranium Recovery from Seawater," NE/SM Thesis.

M.G. Izenson, "Automated PWR Reload Design Optimization," SM/SB Thesis.

K. Kato, "Ray Tracing Analysis of Electron Cyclotron Resonance Heating in Straight Stellarators," SM/SB Thesis.

L.J. Kelly, "The Modelling of Quench Propagation in Small Superconducting Magnets," SM/SB Thesis.

J.C. Lermant, "A New Analysis in the Continuum Theory of Thermal Ignition," SM Thesis.

H.J. Lipschitz, "Uncertainty Propagation in Probabilistic Risk Analysis of High-Level Radioactive Waste Repositories," SM/SB Thesis.

J.L. Maneke, "Thermodynamic Analysis of Transition Core Pool Behavior Following an LMFBR Hypothetical Accident," SM Thesis.

R.C. Marlay, "Industrial Energy Productivity," PhD Thesis.

R.F. Mull, "Exclusion Area Radiation Release During the MIT Reactor Design Basis Accident," SM Thesis.

H. Noda, "Time Dependent Unavailability Analysis of Core Spray Injection System in BWR," NE/SM Thesis.

J.M. Noterdaeme, "Constraints on the Scale of Toroidal Fusion Experiments With Application to the Design of a Helical Axis Stellarator," PhD Thesis.

D.A. Petti, "Postirradiation Iodine Release from $UO_2$ Between 25°C and 700°C," SM/SB Thesis.

M. Szydlo, "Void Distribution in the Vicinity of an Interface," SM Thesis.

J. Varela, "Mass and Momentum Transfer in Uranium-from-Seawater Sorption," SM Thesis.

J.A. Zamora-Reyes, "Policy Analysis on Colombian Uranium Resources," SM Thesis.

The following theses were submitted to the Department of Nuclear Engineering in September 1983:

S.R. Allen, "A Technical Assessment of Uranium Mill Tailings Management," NE/SM Thesis.

B. Ching, "Liquid Droplet Collisions on a Liquid Surface," SM Thesis.

P.J. Gierszewski, "Plasma/Neutral Gas Transport in Divertors and Limiters," ScD Thesis.

K.Y. Huh, "Treatment of Physical and Numerical Diffusion in Fluid Dynamic Simulations," PhD Thesis.

F.A. Kautz II, "Dynamic Analysis of Blast Loading on Reinforced Concrete Structure," NE/SM Thesis.

J.K. Liming, "Time Dependent Unavailability Analysis of Pressurized Water Reactor Standby Safety Systems," SM Thesis.

J. Maldifassi, "A Finite Element Method for Compressible and Incompressible Flow," SM-22/SM-2 Thesis.

V.P. Manno, "Analytical Modelling of Hydrogen Transport in Reactor Containments," ScD Thesis.

W.C.J. Moshier, "The Corrosion Fatigue Behavior of Alloy 600 in Steam Generator Environments," ScD Thesis.

J. Pransky, "Material Requirements for Future Energy Technologies," SM Thesis.

P.B. Roemer, "Optimization of Stellarator Coils," PhD Thesis.

A.A. Shah, "Three Dimensional Characterization of Solid Tumor Microvasculature," PhD Thesis.

M. Sharafi, "Energy Planning for Rural Development, A Case Study of Iran," PhD Thesis.

C.K. Sheeks, "Fatigue Crack Growth Behavior of Inconel X-750 in Simulated BWR Environment," SM Thesis.

The following theses were submitted to the Department of Nuclear Engineering in February 1984:

H. Al-Juwair, "Heavy Ion Sub-Barrier Fusion Investigated Through the 40Ca + 40,44,48 Ca Reactions," PhD Thesis.

F. Bamdad-Haghighi, "Thermal Hydraulic Analysis of a Pressurized Water Reactor During a Total Loss of AC Power Accident," PhD Thesis.

M.S. Brown, "Representing Engineering Risk: A Waste Management Example," SM Thesis.

R.P. Burke, "Economic Risks of Nuclear Power Reactor Accidents," PhD Thesis.

H. daSilva, "Thermohydraulic Analysis of U-Tube Steam Generators," PhD Thesis.

J. DelFavero, "A Safety Study of Modular Pebble Bed High Temperature Gas Cooled Reactors for Process Heat Applications," SM Thesis.

D.B. Ebeling-Koning, "Hydrodynamics of Single- and Two-Phase Flow in Inclined Rod Arrays," PhD Thesis.

E.R. Faillace, "Effects of a High Magnetic Field on the Phase Stability of Iron-Chromium Alloys," SM/SB Thesis.

E. Feijo, "Design of Energy Absorbing Structures for Protection of Nuclear Power Ships," OE/SM Thesis.

S. Garcia, "Modeling of a Once-Through Steam Generator for Operational Safety Systems," NE/SM-2 Thesis.

J.B. Gehret, Jr., "Thermal-Hydraulic Aspects of the Use of Low Enrichment Uranium Fuel in the MIT Research Reactor," SM/SB-2 Thesis.

J. Griffin, Jr., "Few Span Vibration of Steam Generator Tubes With Support Gaps," SM Thesis.

J.W. Johnson, "Monte Carlo Calculation of the Pinch and Bootstrap Neoclassical Transport Coefficients," PhD Thesis.

H.S. Joo, "Resolution of the Control Rod Cusping Problem for Nodal Methods," PhD Thesis.

S.N. Kim, "An Experimental and Analytical Model of a PWR Pressurizer During Transients," PhD Thesis.

J. Lee, "Economic Evaluation of Low-Level Radioactive Waste Volume Reduction Systems," NE/SM Thesis.

S.Y. Lee, "Two-Phase Flow and Heat Transfer in Porous Media," SM Thesis.

M.T. Leonard, "The Effects of a Non-Condensable Gas on Pressurizer Insurge Transients," SM Thesis.

C.T. Mizumoto, "Modeling of Temperature Dependent Structure of Water," SM Thesis.

I.S. Muhtaseb, "Applications of the Average Discontinuity Factors to the Analytical Nodal Method," SM Thesis.

A.C. Onyemaechi, "Heat and Mass Transfer to Falling Water Droplet in a Steam Atmosphere," SM Thesis.

E.N. Paillas, "Lifeline Seismic Risk: Decision Under Uncertainty," SM Thesis.

D.K. Parsons, "The Replacement of Reflectors and Baffles in Nodal Calculations by Albedo Boundary Conditions," PhD Thesis.

H.P. Polenta, "Implementation and Testing of a Microcomputer-Based Fault Detection System," NE/SM Thesis.

A. Raynsford, "Reliability Analysis of the Service Water System of the Angra I Nuclear Power Plant (Brazil)," NE/SM-2 Thesis.

K. Soo Hoo, "Pressure Shift in Carbon Dioxide and Its Isotopes," PhD Thesis.

M.S. Tillack, "Structural Effects of Major Plasma Disruptions on Tokamak Fusion Reactors," PhD Thesis.

O.F.A. Yarman, "Analytical Nodal Theory in Hexagonal Geometry," PhD Thesis.

J.A. Zamora-Reyes, "International Contracts on Natural Resources: Bargaining for Efficiency in Risk and Return Allocation," NE Thesis.

M.W. Zimmermann, "A Critique and Simplification of Nuclear Fuel Cycle Economics Calculations," SM Thesis.

The following theses were submitted to the Department of Nuclear Engineering in June 1984:

J.A. Bernard, Jr., "Development and Experimental Demonstration of Digital Closed-Loop Control Strategies for Nuclear Reactors," PhD Thesis.

A.V. D'Amico, "The Use of Solid Tumor Microvasculature Studies to Explore the Metastatic Process," SM/SB Thesis.

T.J. Downar, "An Integrated Method for Mid-Range In-Core PWR Fuel Management and Core Design," PhD Thesis.

A. Efthimiadis, "Mixed Convection and Hydrodynamic Modeling of Flows in Rod Bundles," PhD Thesis.

T.J. Farish, "A Magnesium Vapor Jet Neutralizer," SM Thesis.

W.R. Ferrara, "Evaluation of 10CFR61 and the Future Implications on Shallow Land Burial Site Selection," SM Thesis.

R.G. Gamino, "Group Collapsing in Fast Reactor Physics Calculations Using Discontinuity Factors," SM Thesis.

D.P. Griggs, "An Advanced Three-Dimensional Coupled Neutronics/ Thermal-Hydraulics Code for Light Water Nuclear Reactor Core Analysis," ScD Thesis.

C.N. Guey, "A Method for Estimating Common Cause Failure Probability and Model Parameters: The Inverse Stress-Strength Interference (ISSI) Technique," PhD Thesis.

V. Iannello, "Feed and Bleed in Pressurized Water Reactors Analyzed Under Uncertainty," SM/SB-22A Thesis.

H.N. Jow, "Prioritization of Nuclear Power Plant Variables for Operator Assistance During Transients," PhD Thesis.

J.E. Kirsch, "Neutron-Induced Track Etch Autoradiography: Studies in Track Detection and Neutron Capture Therapy," PhD Thesis.

M. Kotlarchyk, "Structure and Critical Behavior of Three-Component Microemulsions Studies by Small-Angle Neutron Scattering," PhD Thesis.

R.J. LeClaire, Jr., "Methods of First Wall Structural Analysis With Applications to the Long Pulse Commercial Tokamak Reactor Design," NE/SM Thesis.

E. Montaldo-Volachec, "Computation of Sequential Batch Interactions in Nuclear Fuel Management," NE/SM Thesis.

L. Ottinetti, "A Method for Assessing the Frequencies of Accidents of Radioactive Waste Disposal in Deep Geologic Formations," NE/SM Thesis.

J.F. Perez Mendez-Castrillon, "Reconstruction of Three-Dimensional Flux Shapes From Nodal Solutions," NE/SM Thesis.

M.G. Plys, "An Experimental Investigation of the Core-Concrete Interaction," ScD Thesis.

S.M. Reilly, "Reducing Emission of Argon-41 from the MIT Reactor," SM Thesis.

R. Schechtman, "Risk Assessment of the Beneficial Impact of a Filtered Venting Containment System in a PWR With Large, Dry Containment," PhD Thesis.

P.H. Seong, "Optimization of Waste Age and Canister Diameter for Minimum Waste Management System Cost," SM Thesis.

J.N. Strohmayer, "Preliminary Design of a Tandem Mirror Reactor," SM Thesis.

R.J. Witt, "Computer Techniques for Sensor Validation During EBR-2 Natural Circulation," SM Thesis.

F.M.G. Wong, "Stresses and Flexibilities for Pressure Vessel Attachments," SM/SB-22A Thesis.

E. Yachimiak, Jr., "Safety Analysis of Water-Cooled Liquid Lithium Breeder Module Designs," SM Thesis.